

# ISS-RAD Fast Neutron Detector (FND) ACO On-Orbit Neutron Dose Equivalent and Energy Spectrum Analysis Status

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on behalf of the ISS-RAD science team



Ryan Rios

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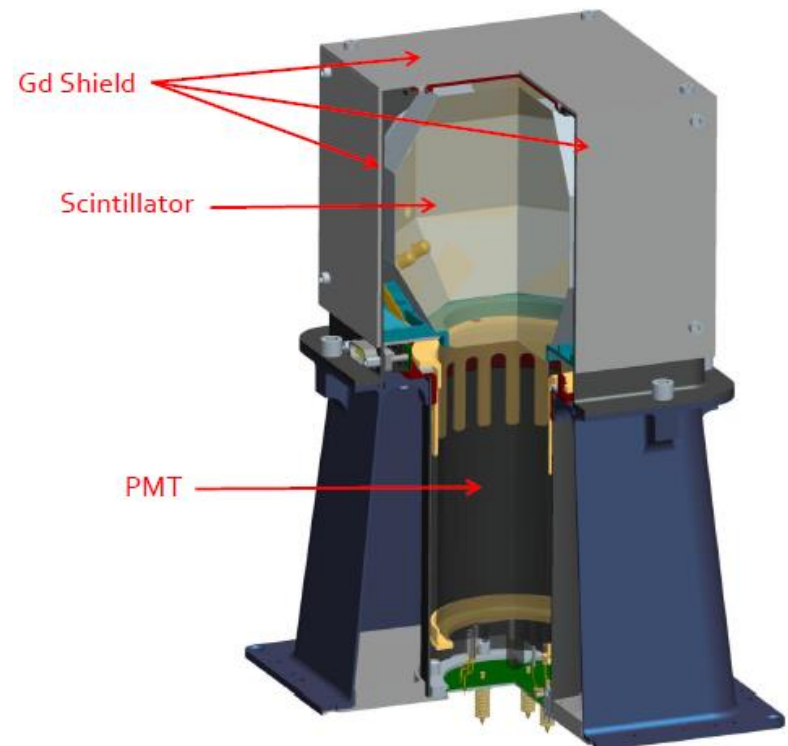
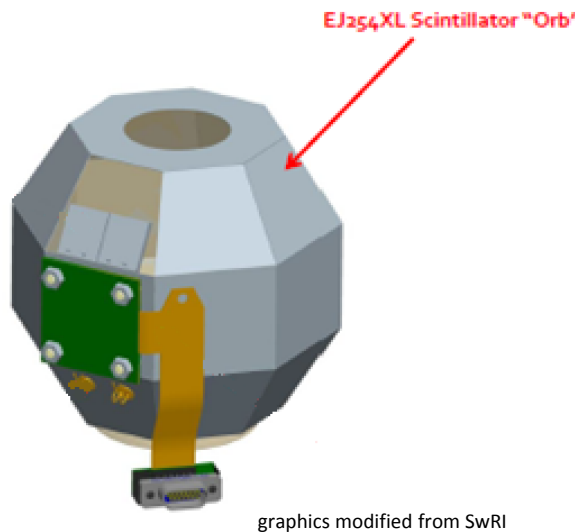
Cary Zeitlin

09/7/16



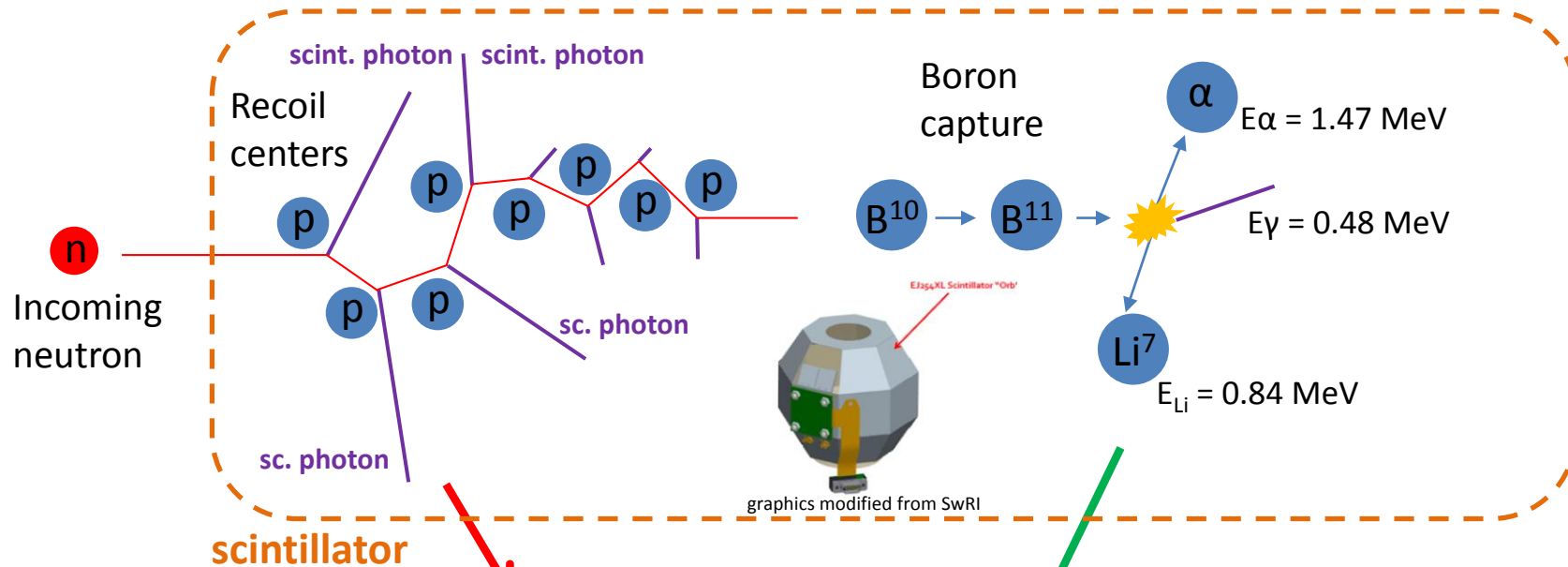
## Outline:

1. Introduction: Basic Interpretation of FND Data
2. Orbital Data Analysis Methods (Online, Offline Light, Offline Heavy)
3. Ground Verification of Analysis Methods
4. Raw Orbital Data
5. ACO Results, Status
6. Forward Work

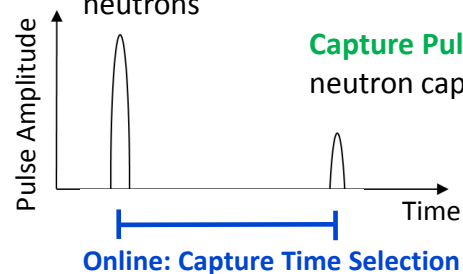


# 1. Introduction: Detection/Selection Mechanism: Boron-loaded Scintillator

- Neutrons deposit energy in plastic scintillator, some captured by  $^{10}\text{B}$  atoms:

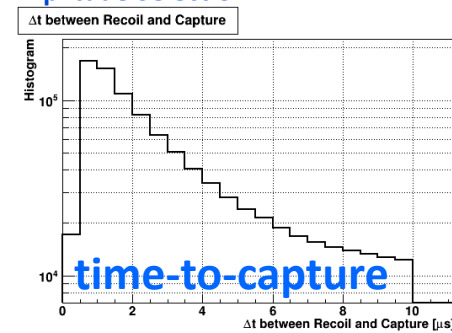


**Recoil Pulse:** sum of light signals produced during deceleration of neutrons



**Capture Pulse:** light produced by neutron capture on boron

**Online: Capture Amplitude Selection**

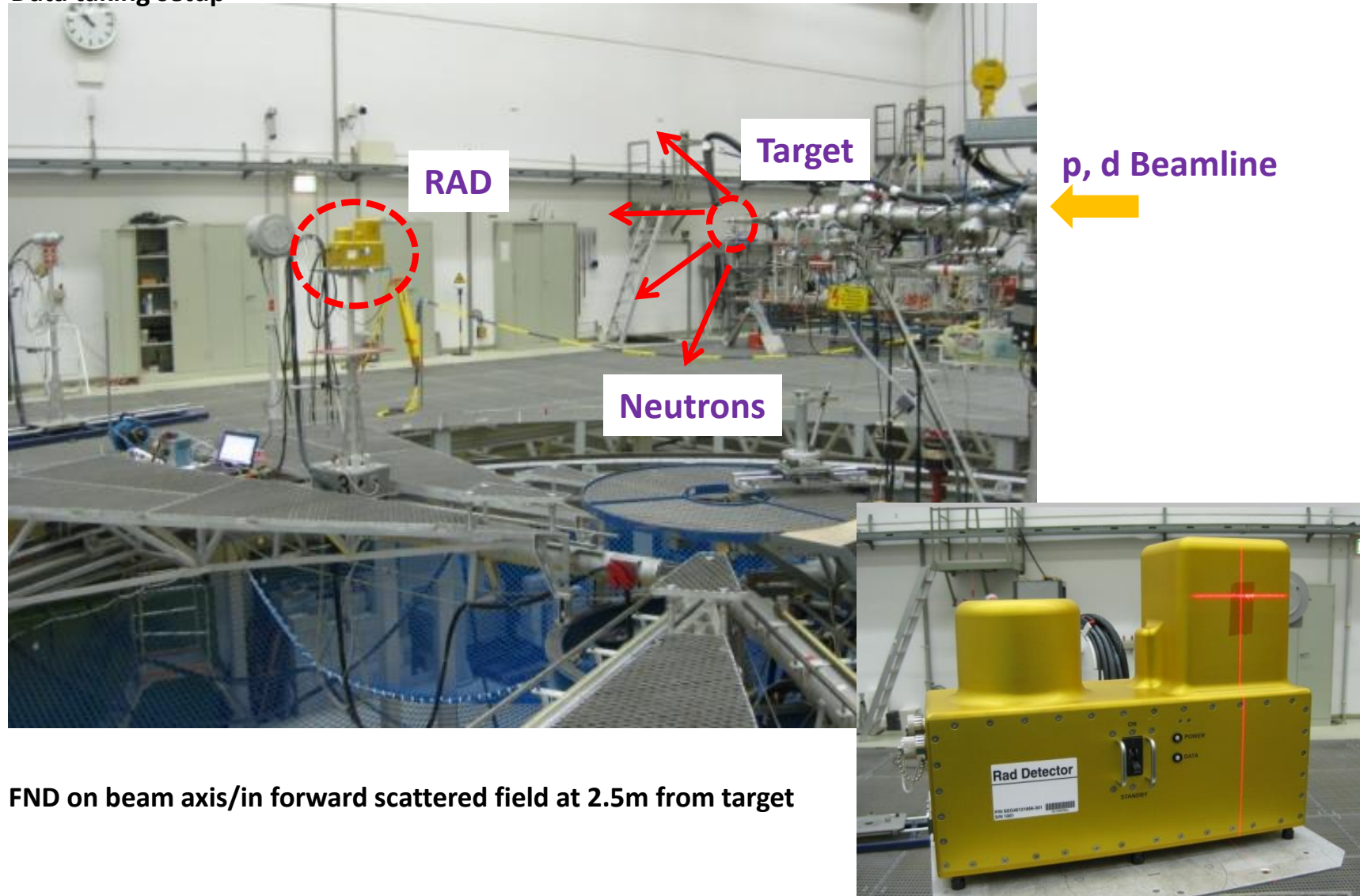


- Measurements of **recoil** and **capture** photon signals and **time-to-capture**:

# 1. Introduction: Response Spectrum Shape

- 'Monoenergetic' neutron calibration ( $\Delta E < 5\%$ ) at PTB, Germany:

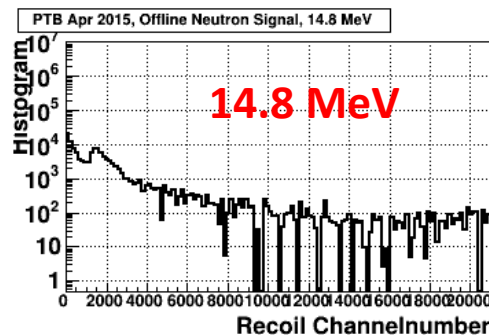
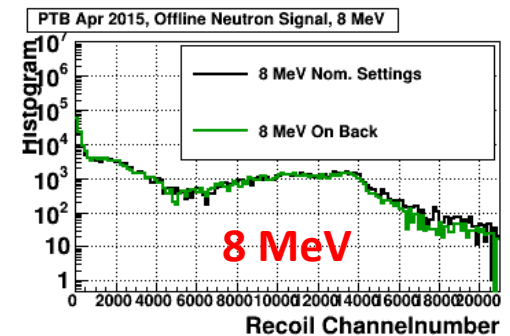
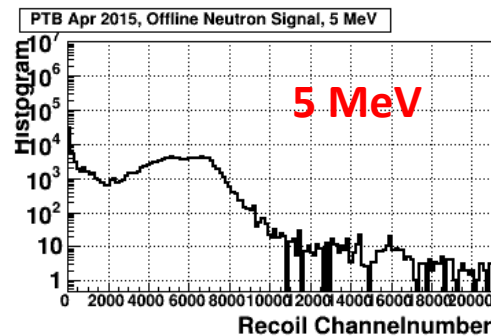
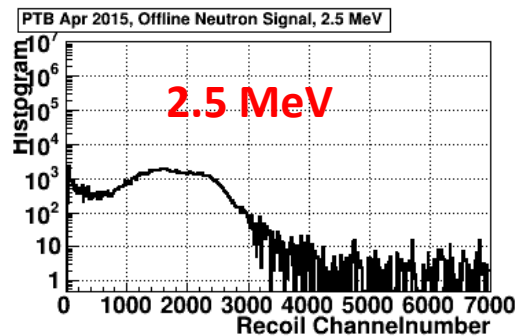
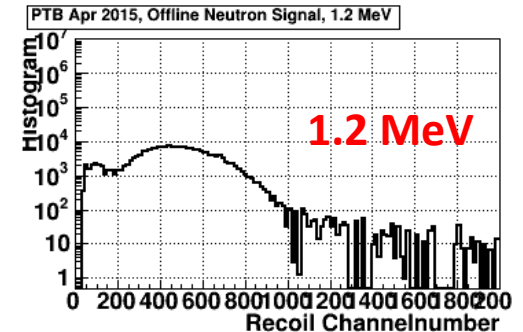
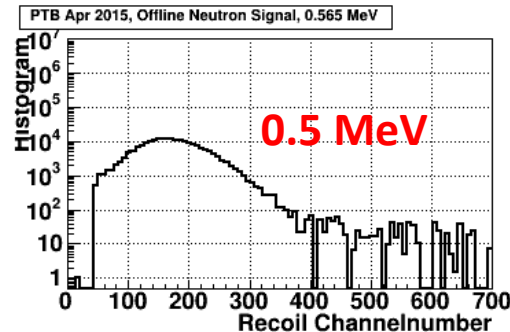
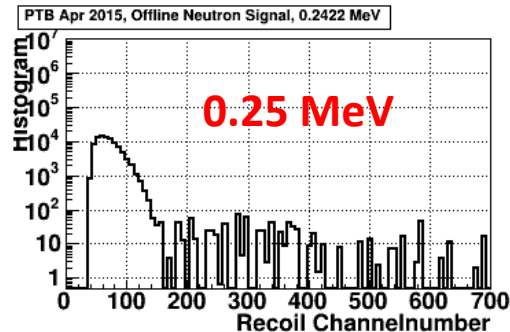
## Data taking setup



FND on beam axis/in forward scattered field at 2.5m from target

# 1. Introduction: Response Spectrum Shape

- Filtered ADC spectrum in response to monoenergetic neutron fields (after background subtraction):



# 1. Introduction: Scintillation Light Creation/Propagation: Light Function Formalism

- Shape of response spectra dominated by:

**a) Multiple scattering** of neutron with scintillator material nuclei: multiple pulses of scintillation light per neutron

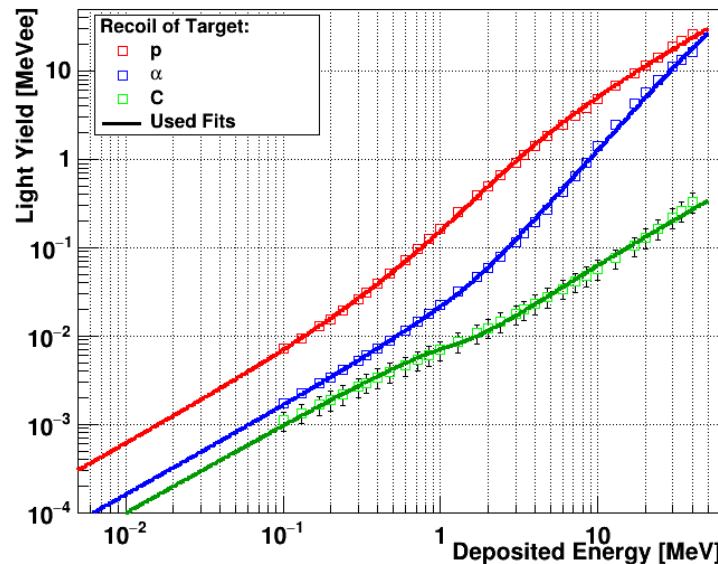
**b) Scintillation light quenching** (ionization quenching- Birk's law): nonlinear amount of collected scintillation light per interaction depending on energy deposit & scattering target



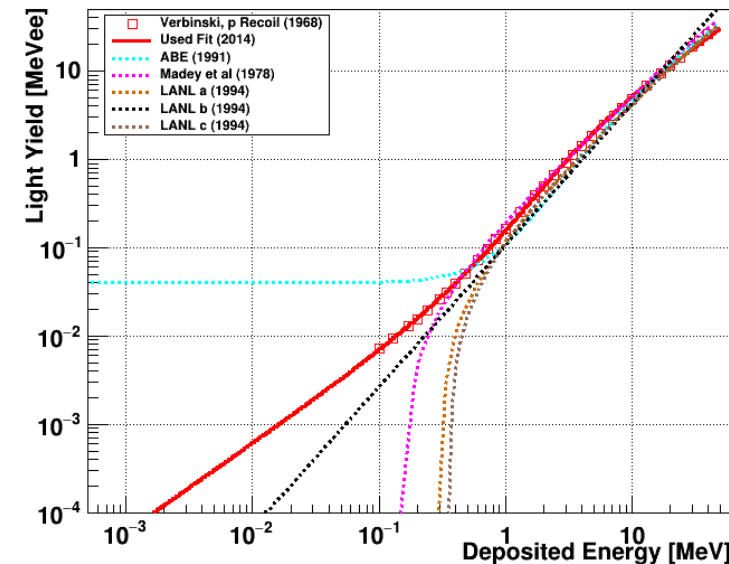
**Even monoenergetic neutrons create broad distribution in light deposit/FND recoil spectra.**

- Approach describing scintillation light generation in multiple scattering: Light function formalism
- Measurements/parameterization of light functions: Verbinski et al, 1968 (liquid scintillator):

Neutron Deposited Energy to Light-Yield Relations, Verbinski et al 1968, Liquid Organic Scintillator



Neutron Light Functions Used in Literature



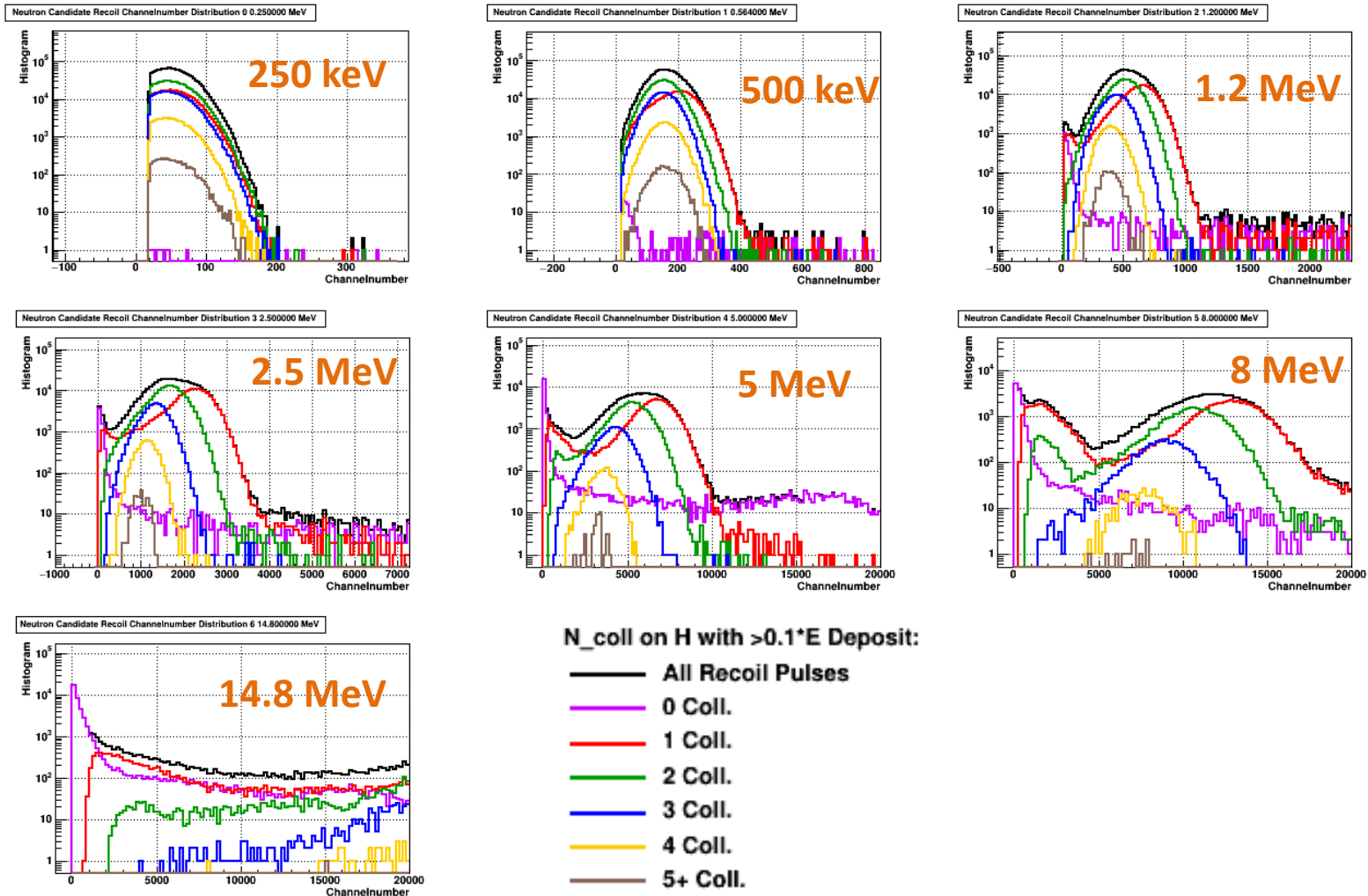
Literature:  
Neutron recoils on...

V.V. Verbinski et al,  
NIM 65 (1968) 8 ff

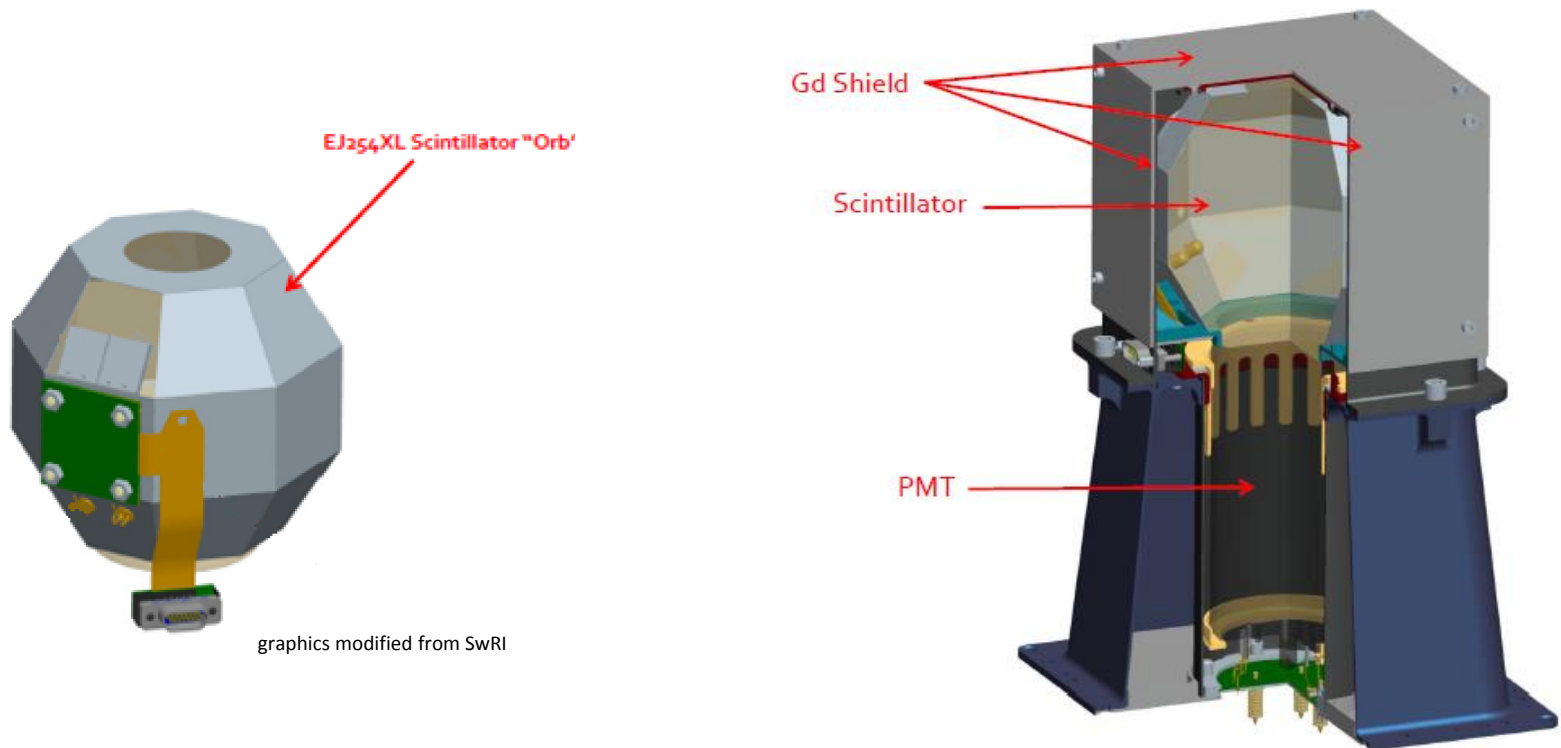


# 1. Introduction: Scintillation Light Creation/Propagation: Light Function Formalism

- Example: End-to-end FND simulation (MCNP-PoliMi and FND signal processing algorithms) for monoenergetic neutron fields at PTB
- Spectral shape driven by number of high energy deposit neutron collisions off hydrogen:



## 2. Analysis Methods





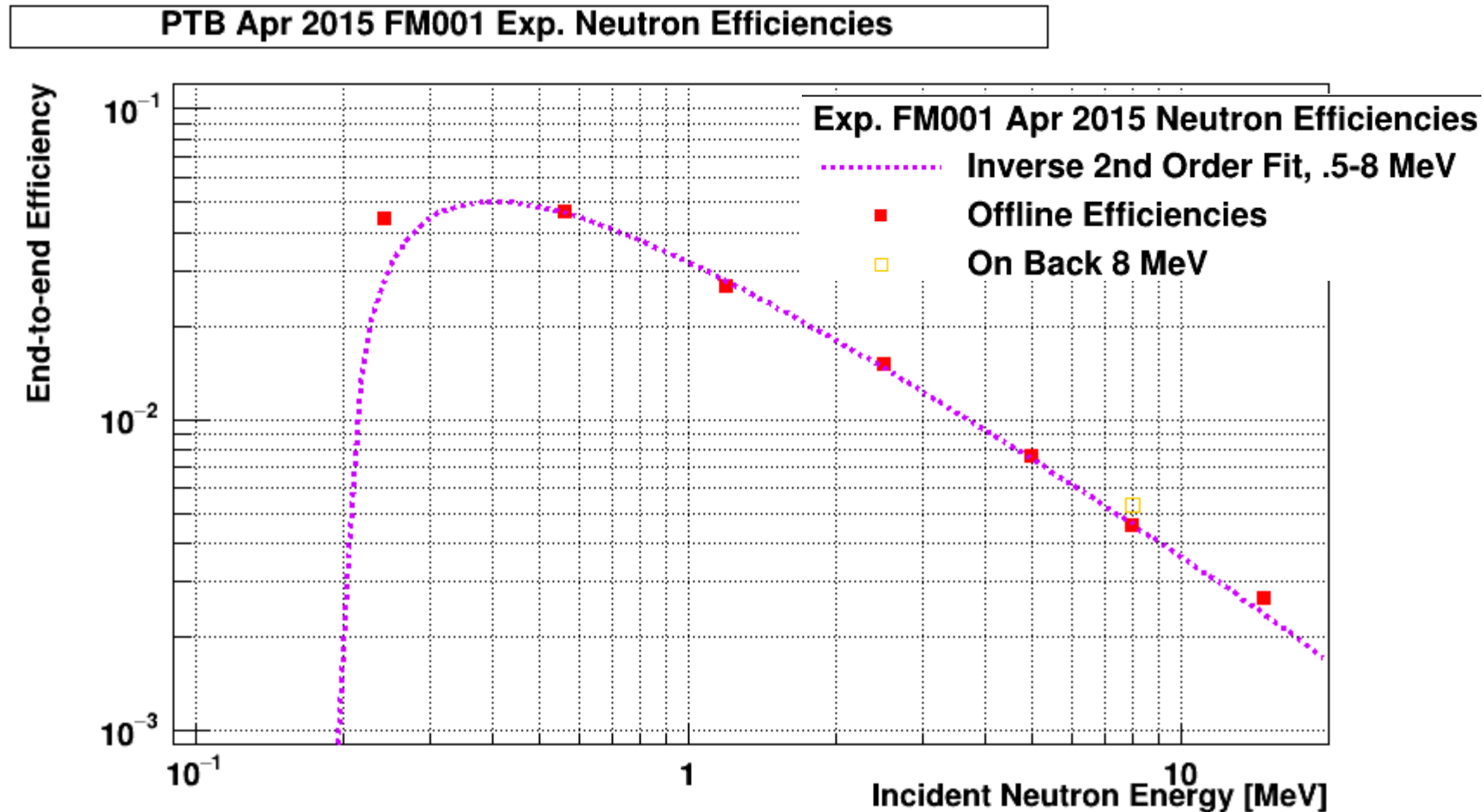
## 2. Analysis Variants to Extract Dose Equivalent and Neutron Energy Spectrum

- Different analysis methods depending on computational resource availability
- Dose equivalent ( $H^*(10)$ ) calculated with ICRP 74 conversion factors

Analysis	Computational Complexity	Output	Analysis Methods
a) On-board	Simple	Dose equivalent	- Conversion factors for each recoil amplitude bin
b) Ground Light	Moderate	Dose equivalent	- Background subtraction - Conversion factors for each recoil amplitude bin
c) Ground Heavy	Complex	Flux and dose equivalent energy spectra	- Background subtraction - Regularized unfolding into energy spectrum

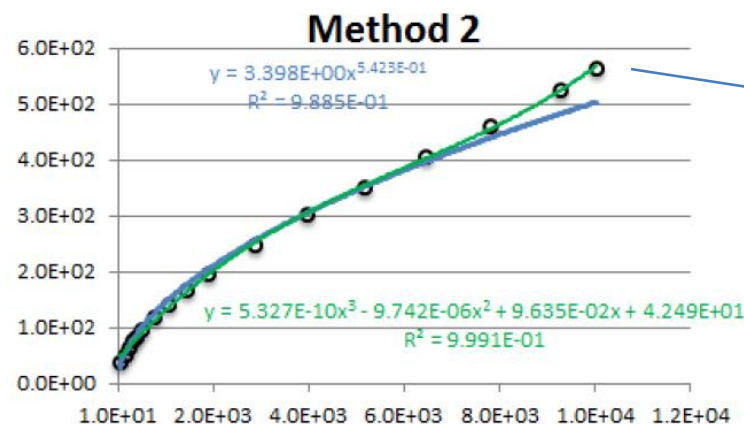
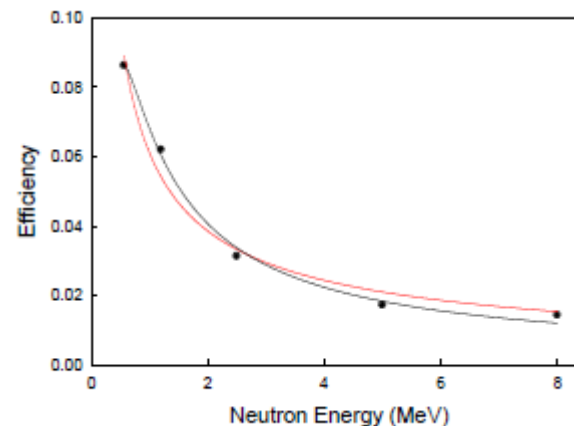
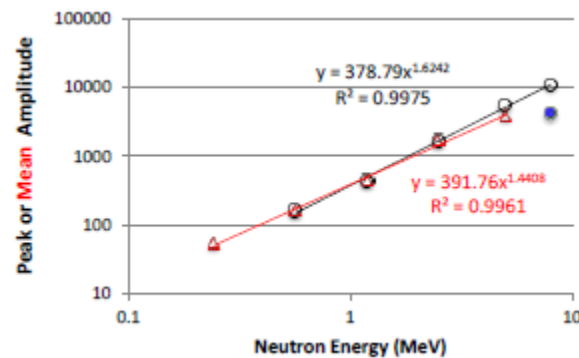
## 2. Efficiencies

- Use exp efficiencies directly from Apr PTB 2015 data from 0.5 to 8 MeV
- For interpolated energies, use inverse square law fit of 0.5-8 MeV data (Cary Z.)
- Values depending on cuts in background subtraction and recoil/capture spectrum



## 2. On-Orbit Analysis (Cary Z.)

- Conversion factors for each recoil bin amplitude to dose equivalent ( $H^*(10)$ )
- Factors derived from:
  - \* Fit of PTB recoil spectra means with power law
  - \* Fit PTB efficiency with inverse second order parameterization
  - \* Multiply recoil and efficiency fit with ICRP dose conversion factors in each recoil bin

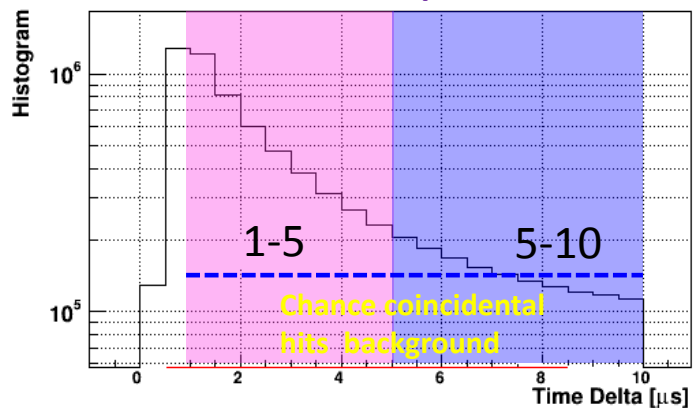


Conversion Factors

## 2. Background/Chance Coincidence Subtraction

- Poisson time correlation between recoil and capture pulses for B10 capture event allow to subtract backgrounds (exponential process)
- Oversubtraction ensures all backgrounds subtracted; rejected neutron pairs recovered via efficiency correction
- Performed in both offline analyses

Delta T Capture



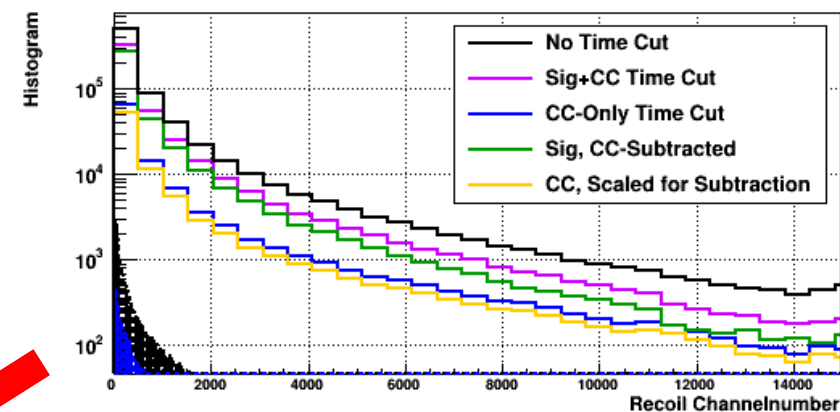
Signal + cc

cc

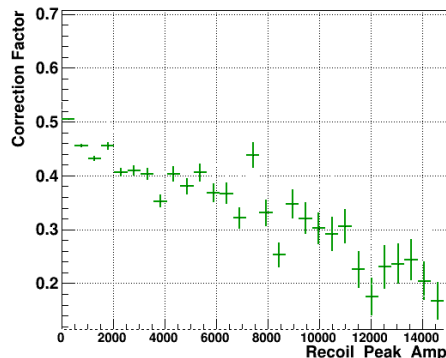


Signal  
Total

Recoil Channelnumber



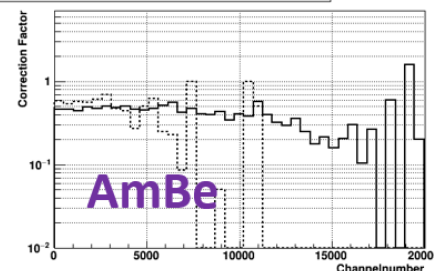
Chance Coincidence Subtraction Factors



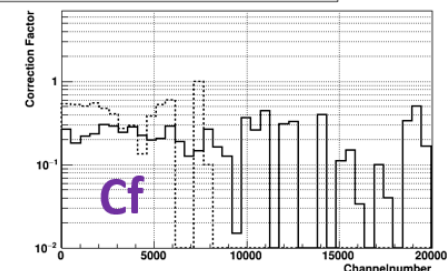
Background fractions for ground test sources:

- \* AmBe 40-50%
- \* Cf 80% (50-60% indirect radiation-only)

AmBe Recoil Histogram Calibration Data Background Correction Factors



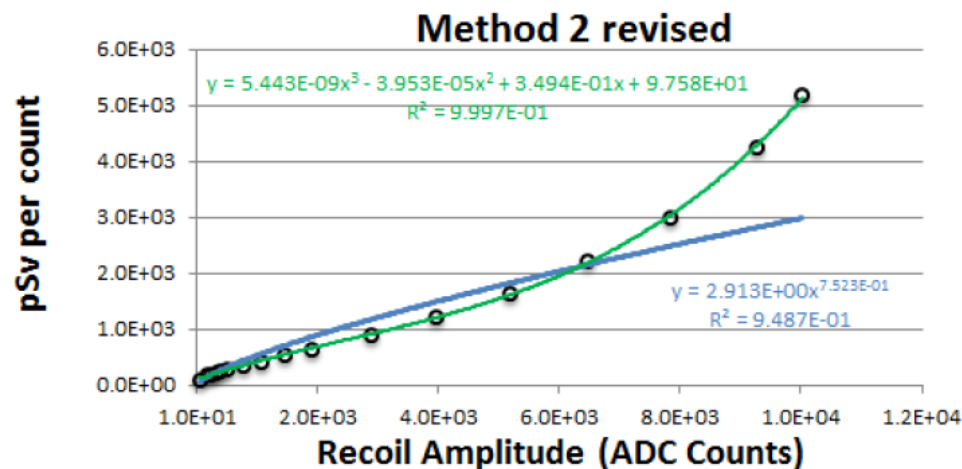
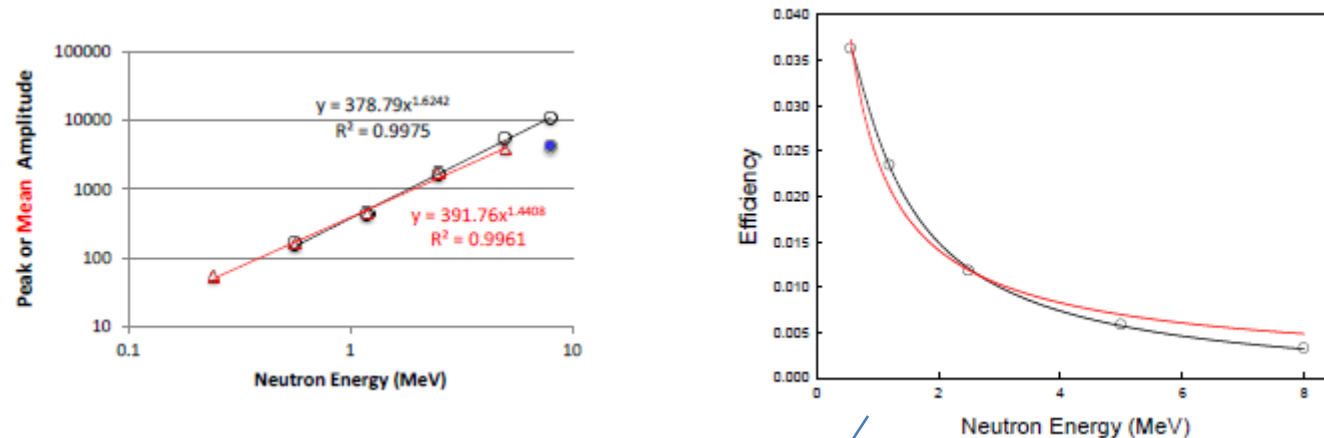
Cf Recoil Histogram Calibration Data Background Correction Factors



For chance coincidence subtraction  
of cyclic recoil histograms

## 2. Offline Light Analysis (Cary Z.)

- Fit of PTB background-subtracted recoil spectra means with power law
- Fit PTB efficiency with inverse second order parameterization
- Multiply recoil and efficiency fit with ICRP dose conversion factors in each recoil bin



## 2. Unfolding Procedure (Martin L.): Regularized SVD Unfolding

A. Hoecker, V. Kartvelishvili, NIM A372, 469 (1996)  
[arxiv:hep-ph/9509307]

- Uncertainties on data distributions and response matrix

=> use regularized, singular vertex decomposition-based unfolding algorithm (ROOT: TSVDUnfold)

### - Advantages:

\* correct treatment of uncertainty-equipped input quantities (detector response matrix, input distribution)

\* full uncertainty propagation; fast

### - Limitations:

\* 'strength' of regularization described by free parameter, needs to be determined from characteristics of orbit data, simulation and ground test data (systematic uncertainty)

\* dependence on input distribution (not found strong)

general problem  
formulation:

$$\hat{A} x^{\text{ini}} = b^{\text{ini}}, \quad \sum_{i=1}^{n_b} \left( \sum_{j=1}^{n_x} \hat{A}_{ij} x_j - b_i \right)^2 = \min$$

but: Experimental uncertainties

$\Delta b \neq 0$

$$\sum_{i=1}^{n_b} \left( \frac{\sum_{j=1}^{n_x} \hat{A}_{ij} x_j - b_i}{\Delta b_i} \right)^2 = \min, \quad (\hat{A}x - b)^T B^{-1} (\hat{A}x - b) = \min$$

Rescaling and  
regularization:

$$(\tilde{A} w - \tilde{b})^T (\tilde{A} w - \tilde{b}) + \tau \cdot (C w)^T C w = \min$$

regularization parameter: chosen from rank of  
response matrix/problem

-> need response matrix for given recoil channelnumber and chosen neutron energy binning



## 2. Unfolding Neutron Energy Binning

### - Neutron energy binning:

\* low and high limits: approach from detector side:

@ **lower limit: 200 keV** (electronics lower pulse cutoff/armoring threshold)

@ **upper limit: 8.5 MeV** (corresponding pulses start to saturate 12-bit ADC)

\* bin width:

@ FND orbit data histograms hardcoded to 512 channel width (29 bins)

@ Low energy challenge: light function nonlinearity: first recoil bin contains most of all < 1 MeV neutrons; 1.59 MeV centered in second bin

@ Unfolding requires benefits from unique response matrix rows- recoil spectrum of neighboring energy bins should 'peak' in different recoil bins

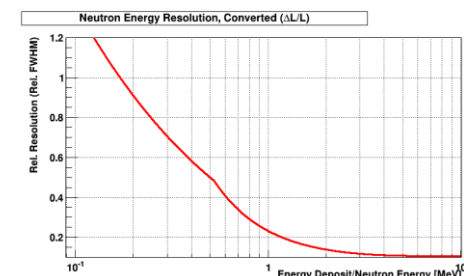
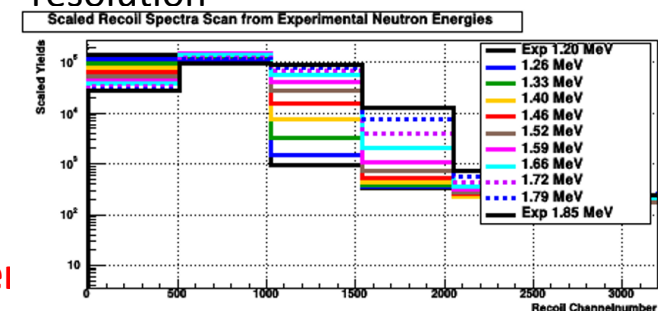
@ Unfolding algorithm reacts positively to similar neutron energy bin size

@ Choose high energy bin widths following detector resolution (determined from light function calibration), width = 2 \* resolution

Lower Lim	Center	Width
0.2	0.664	0.927
1.127	1.59	0.927
2.054	2.403	0.698
2.752	3.101	0.698
3.45	3.913	0.925
4.375	5	1.375
5.75	6.5	1.5
7.25	8	1.5

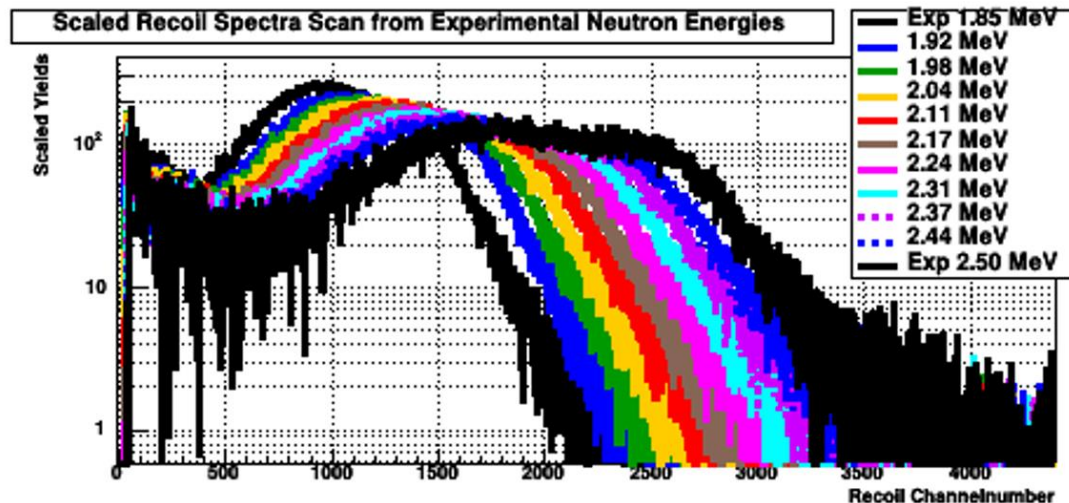
recoil binning-drive

energy resolution-driven

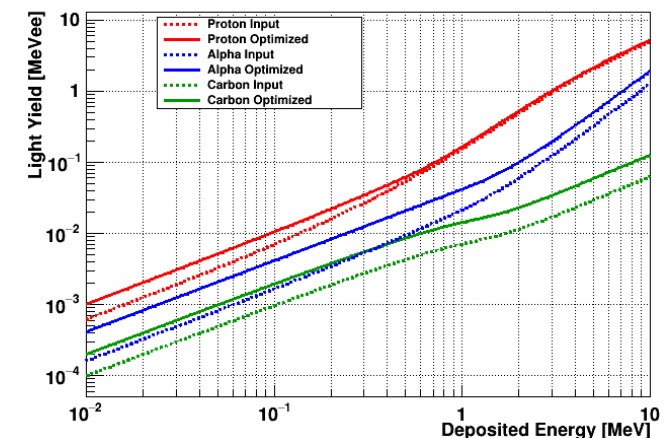


## 2. Response Matrix Assembly

- Were unable to reproduce experimental PTB datasets with sufficient accuracy through MCNP-based simulation
- Create response matrix instead by 'scaling' available experimental monoenergetic distributions
- All bin centers straddled by available experimental data; assumption is that spectra change continuously with energy (supported by simulation results): Along MCNP-calibrated light function,
  - a) scale down experimental distribution for **higher energy**
  - b) scale up exp distribution from **lower energy**
  - c) average



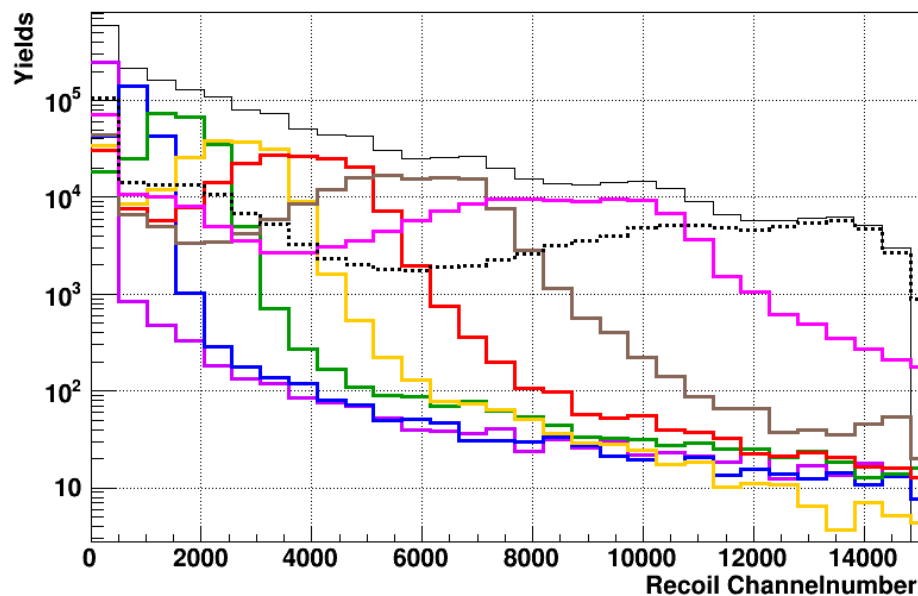
**Neutron Light Conversion Functions**



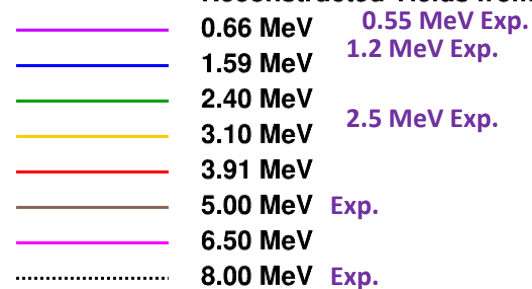
## 2. Response Matrix Assembly

- Response matrix and row slices from scaled experimental distributions

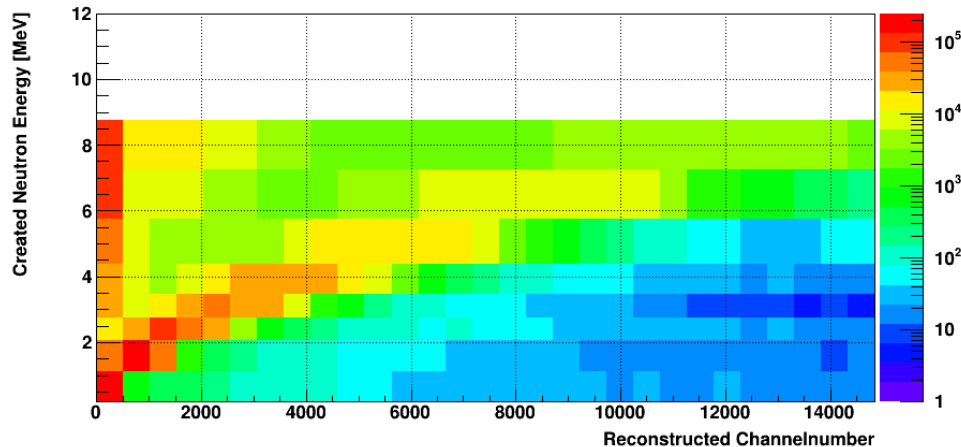
Reconstructed Yields from Created Neutrons



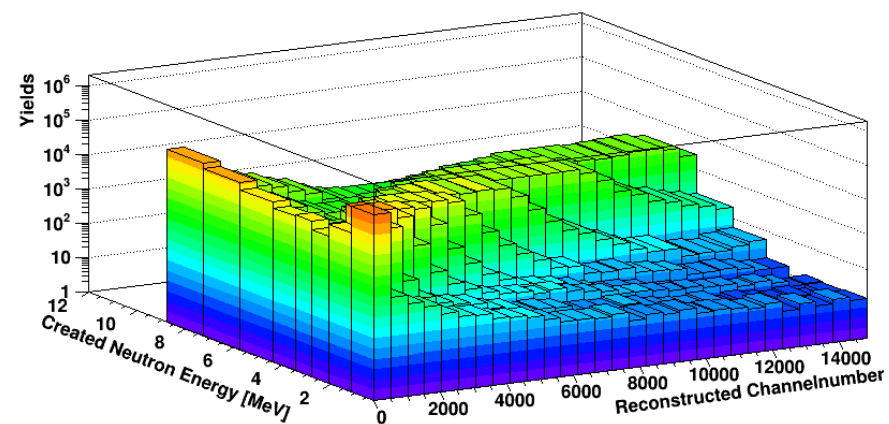
Reconstructed Yields from All Created Neutrons



FND Response Matrix



FND Response Matrix



## 2. Response Matrix Assembly

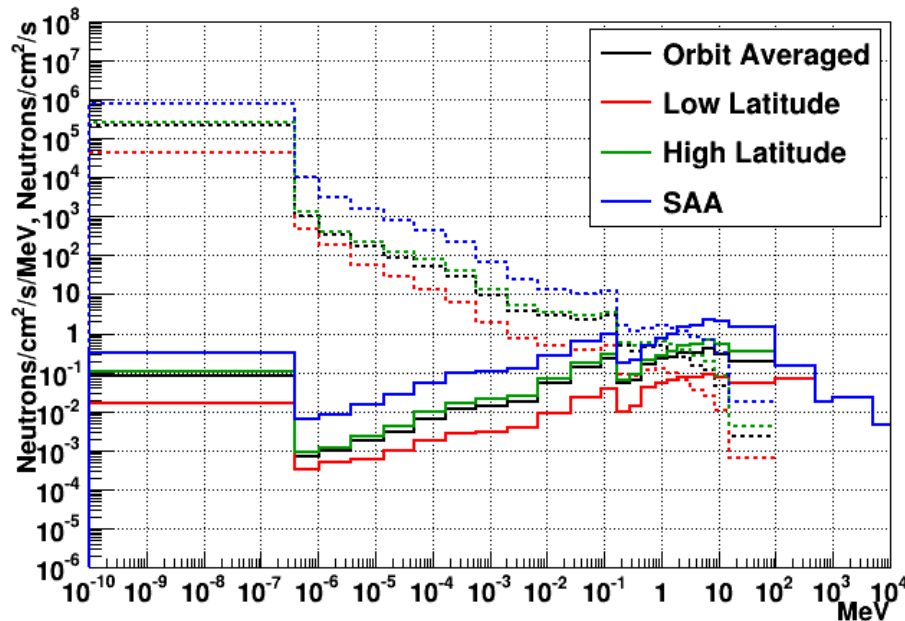
- Can choose 'input spectrum' freely: weighting of columns of response matrix relative to each other
- Choose 'input spectrum' close to expected truth:
  - \* Koshiishi et al, published 2007 (data from 2001);
  - \* three data points filled for energies [100 MeV; 10 GeV] from simulation
- Integral orbit averaged flux (black line):
  - \* thermal to 200 keV:  $\sim 0.6 \text{ n/cm}^2/\text{s}$ ,  $> 8.5 \text{ MeV}$ :  $0.6 \text{ n/cm}^2/\text{s}$
  - \* total  $\sim 3.0 \text{ n/cm}^2/\text{s}$

H. Koshiishi et al,  
Rad. Meas. 42 (2007), 1510ff

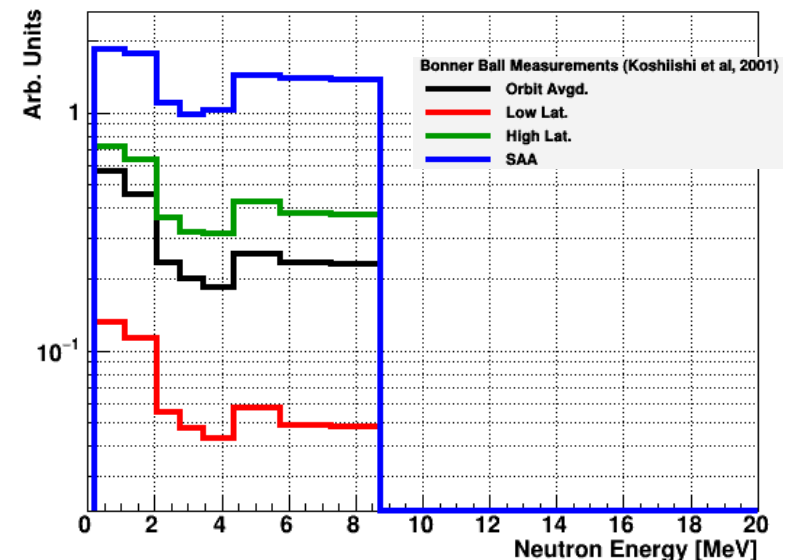
Rebin



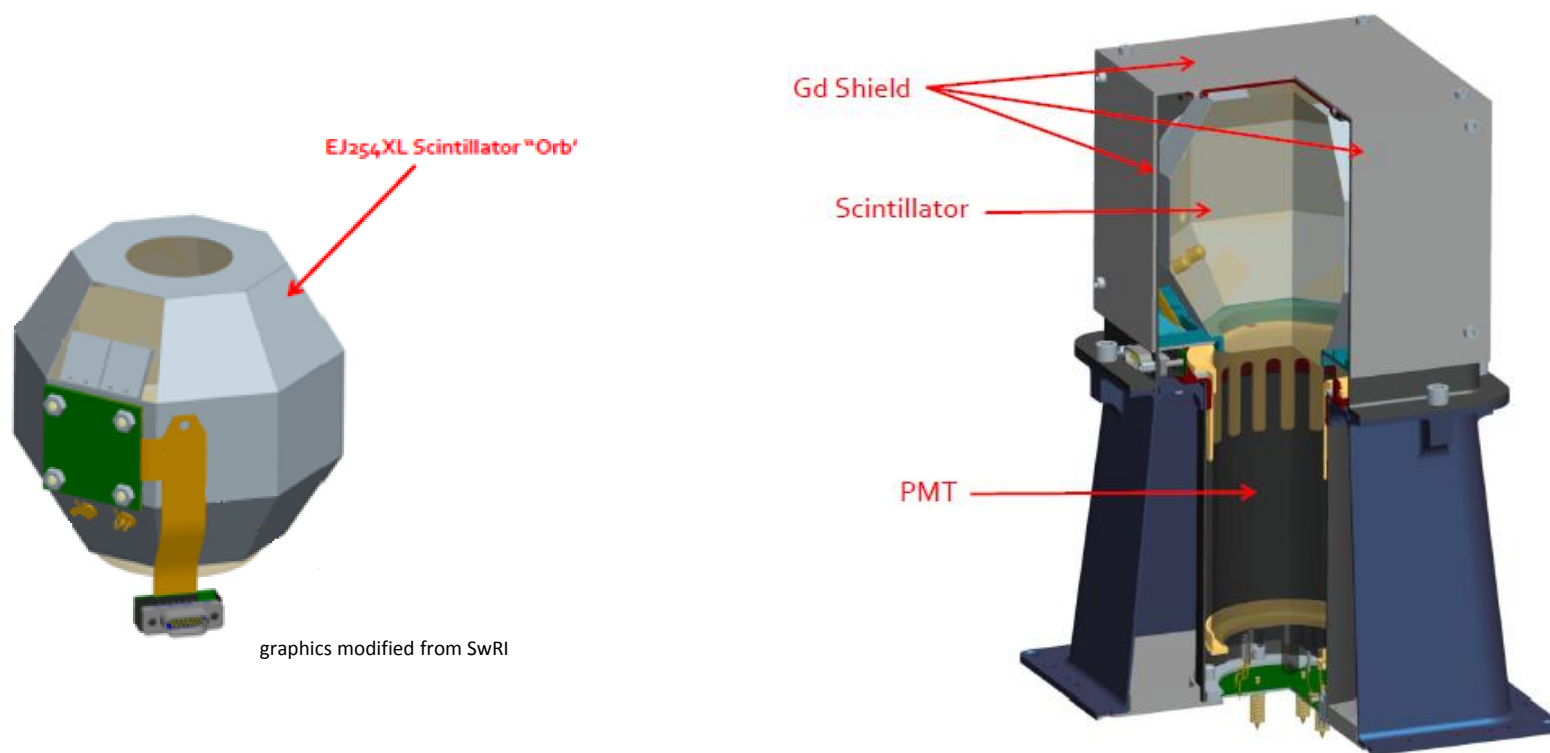
2001 ISS Simulated (Armstrong, Colborn) and Bonner Ball Exp, Koshiishi et al, Neutron Fluxes



Normalization of Response Matrix Projections

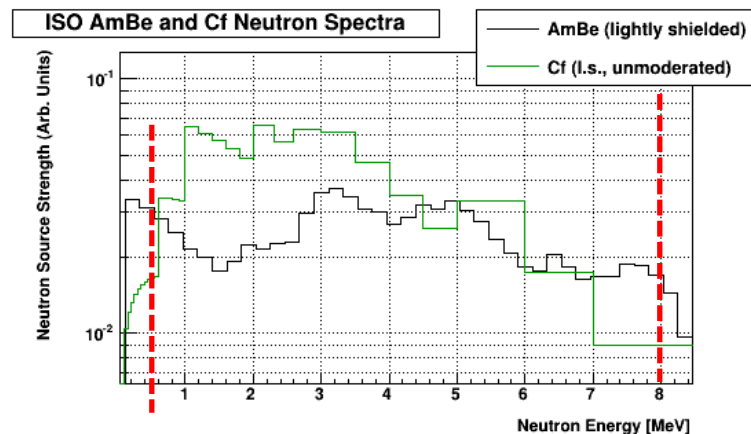


### 3. Ground Verification of Analysis Methods



### 3. Ground Verification- PTB Source Runs

- AmBe and Cf-254 source runs in PTB precision source bunker; corrections for effective depth and FND energy acceptance
- Extract reference dose and spectra from ISO distributions for 0.5 to 8 MeV energy range
- True rate: 0.708  $\mu\text{Sv}/\text{min}$  AmBe, 0.495  $\mu\text{Sv}/\text{min}$  Cf
- Online: 0.673  $\mu\text{Sv}/\text{min}$  AmBe, 1.091  $\mu\text{Sv}/\text{min}$  Cf
- Offline light: 0.696  $\mu\text{Sv}/\text{min}$  AmBe, 0.537  $\mu\text{Sv}/\text{min}$  Cf
- Already see online algorithm sensitivity to chance coincidence pulses due to impossibility to perform background subtraction

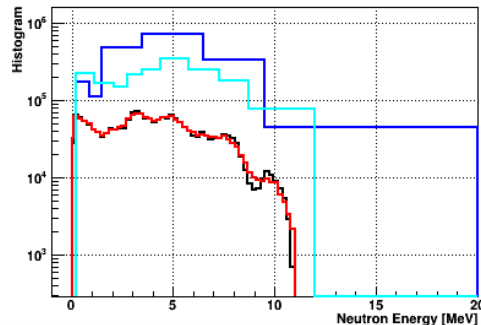




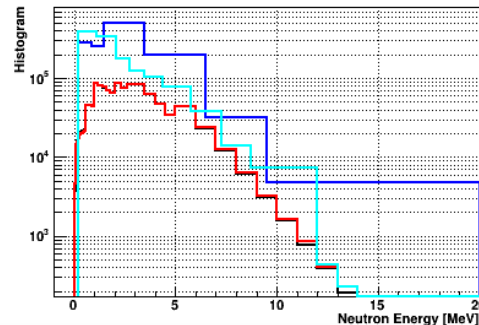
### 3. Ground Verification- PTB Source Runs

- AmBe and Cf-254 source runs in PTB precision source bunker; corrections for effective depth and FND energy acceptance
- Offline heavy:
  - \* Subtraction of room return to compare to ISO spectra
  - \* AmBe: unfolding results within 10% of AmBe in all bins
  - \* Cf: within 26%: possible reason for larger deviation is rapid decay of Cf spectrum in energy range (factor 30), vs AmBe and Orbital < 3
- Test unfold of artificial combination sample of monoenergetic sources within 30% on non-empty bins

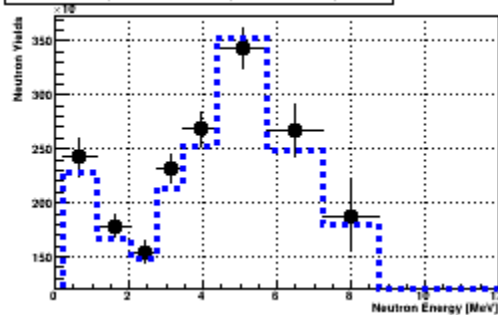
ISO AmBe Neutron Energy Spectrum



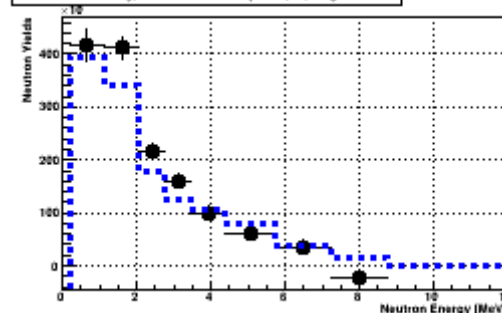
ISO Cf Neutron Energy Spectrum



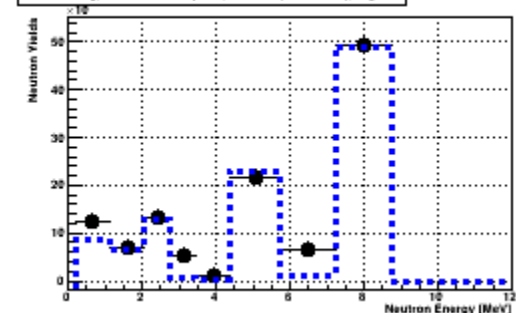
Post Unfolding, Eff. Corr Neutron Spectra, AmBe, kregids 6



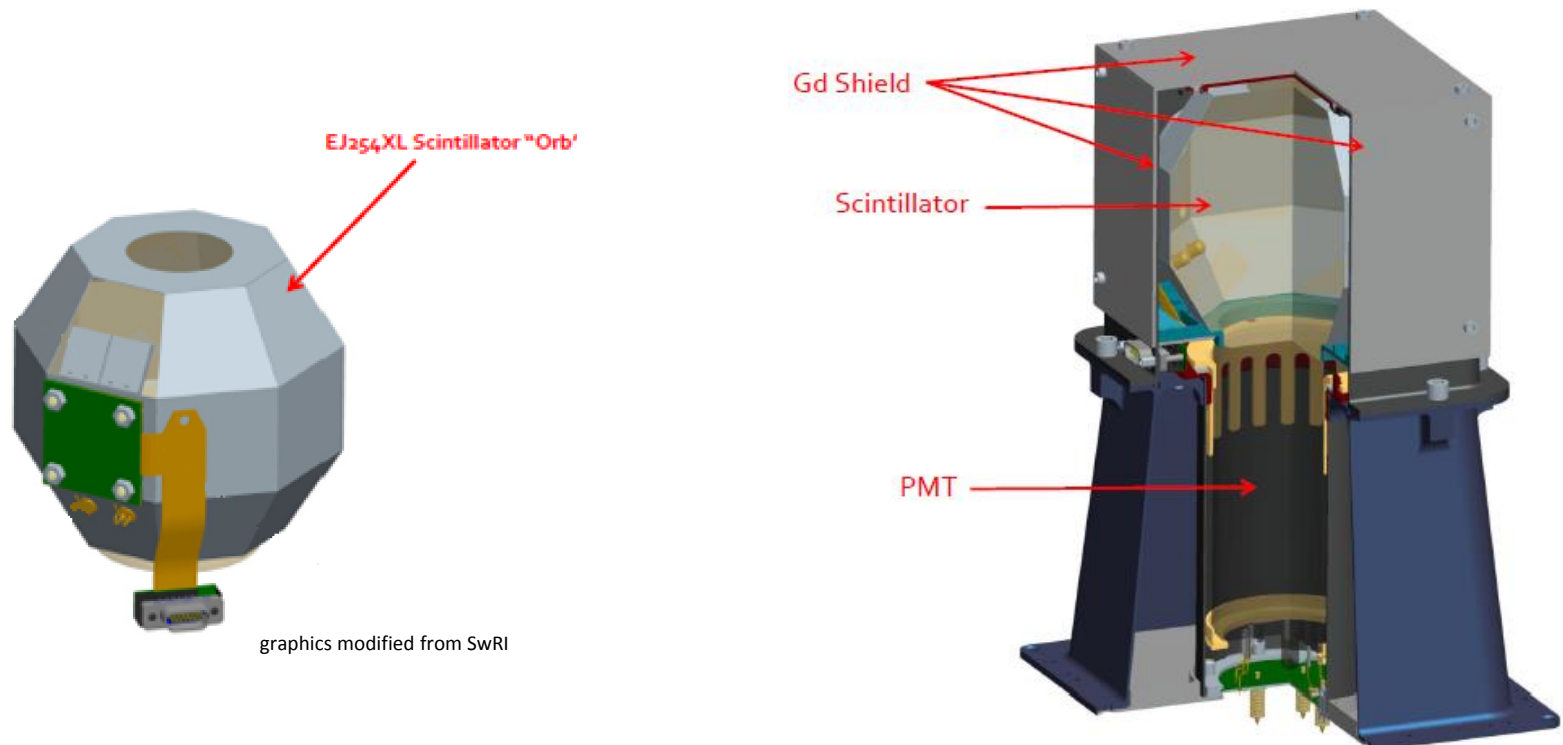
Post Unfolding, Eff. Corr Neutron Spectra, Cf, kregids 7



Post Unfolding, Eff. Corr Neutron Spectra, Combined (Unsmoothed), kregids 8

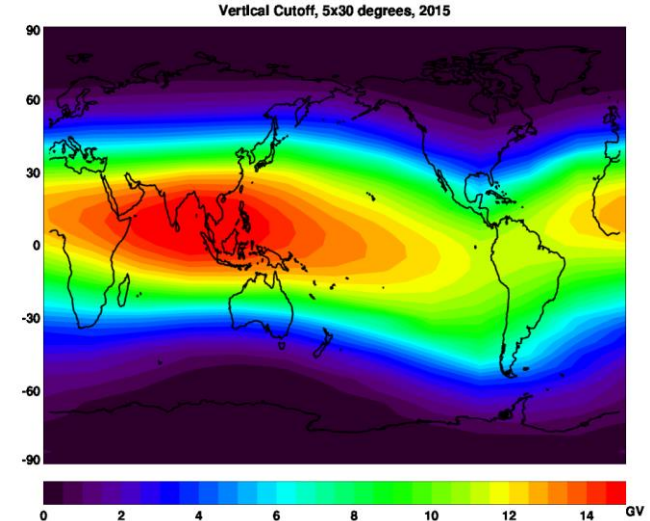
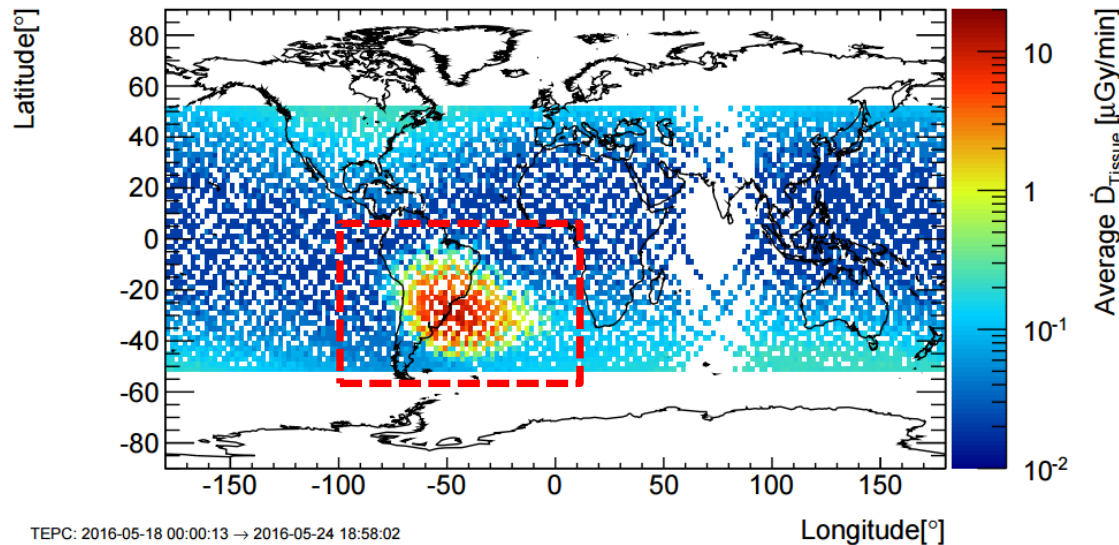


## 4. Orbital Raw Data



## 4. Longitude/Latitude Binning

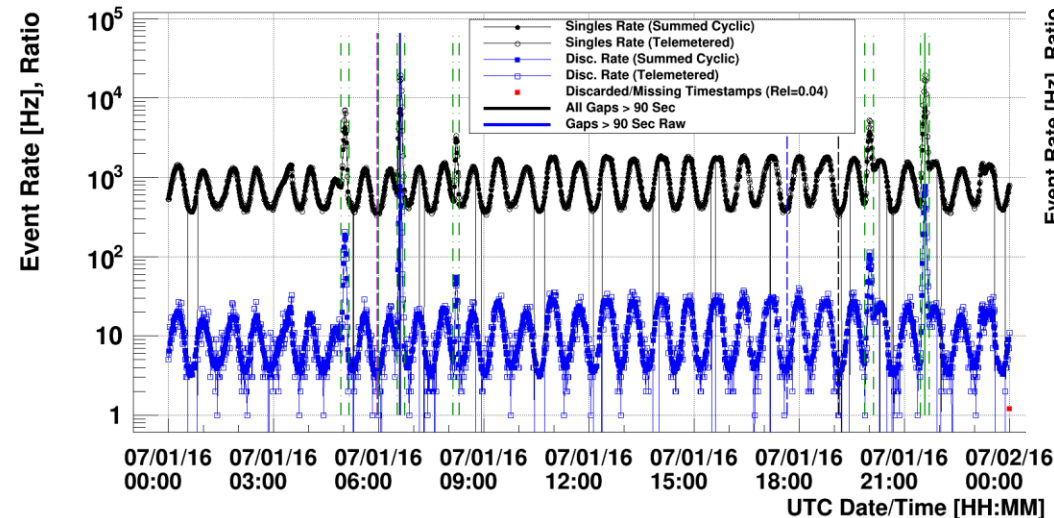
- SAA selection: use cuts: lon in  $[-90;10]$ ; lat  $< 10$  && FND singles rate derivative cut
- Koshiishi et al selections: 'high latitude'  $< 1$  GV geomagnetic rigidity cutoff,  $>13$  GV for 'low latitude' (from CREME 86)
- To determine rigidity per data point, use 2015 lookup table from LaRC with looser cuts for better statistics: high lat  $<3$  GV, low lat  $\geq 11$  GV
- Comparisons for FND vs Koshiishi et al low and high lat will be apples to oranges as magnetic environment changed in last 20-30 years



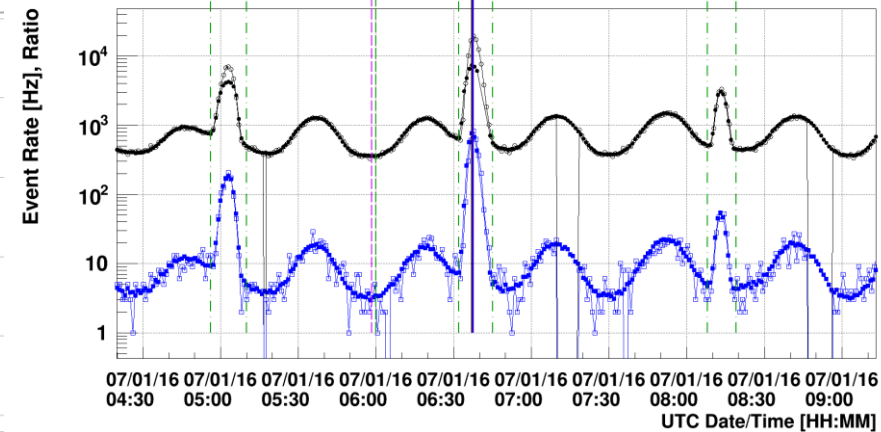
## 4. Exemplary Raw Orbit Data

- 24 hr slice from 7/1/16 with largest SAA pass to date
- Shown are singles and discriminated rates
- Discriminated rate increases by factor 30-40 inside SAA compare to magnetically unshielded areas outside of SAA

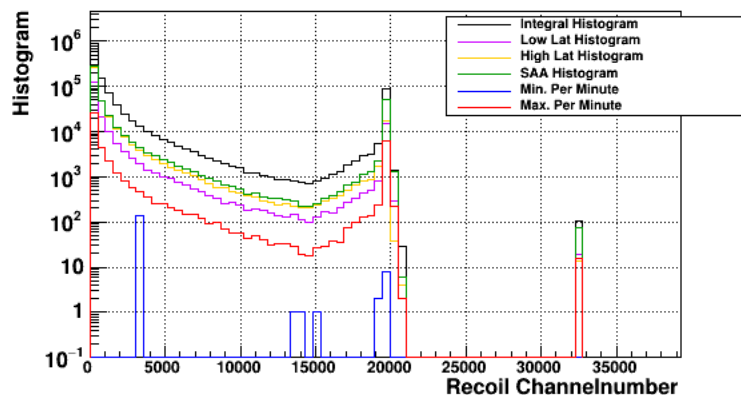
Singles and Disc Rates, 2016-07-01 00:00:00 to 2016-07-02 00:00:00, Cutlevel 1



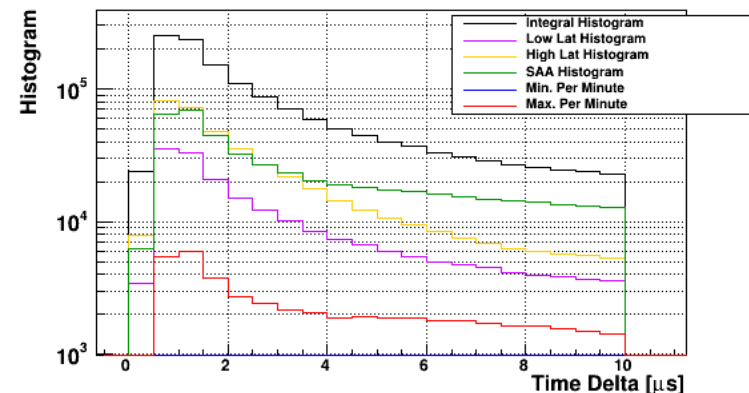
Singles and Disc Rates, 2016-07-01 00:00:00 to 2016-07-02 00:00:00, Cutlevel 1



Recoil, 2016-07-01 00:00:00 to 2016-07-02 00:00:00, Cutlevel 1



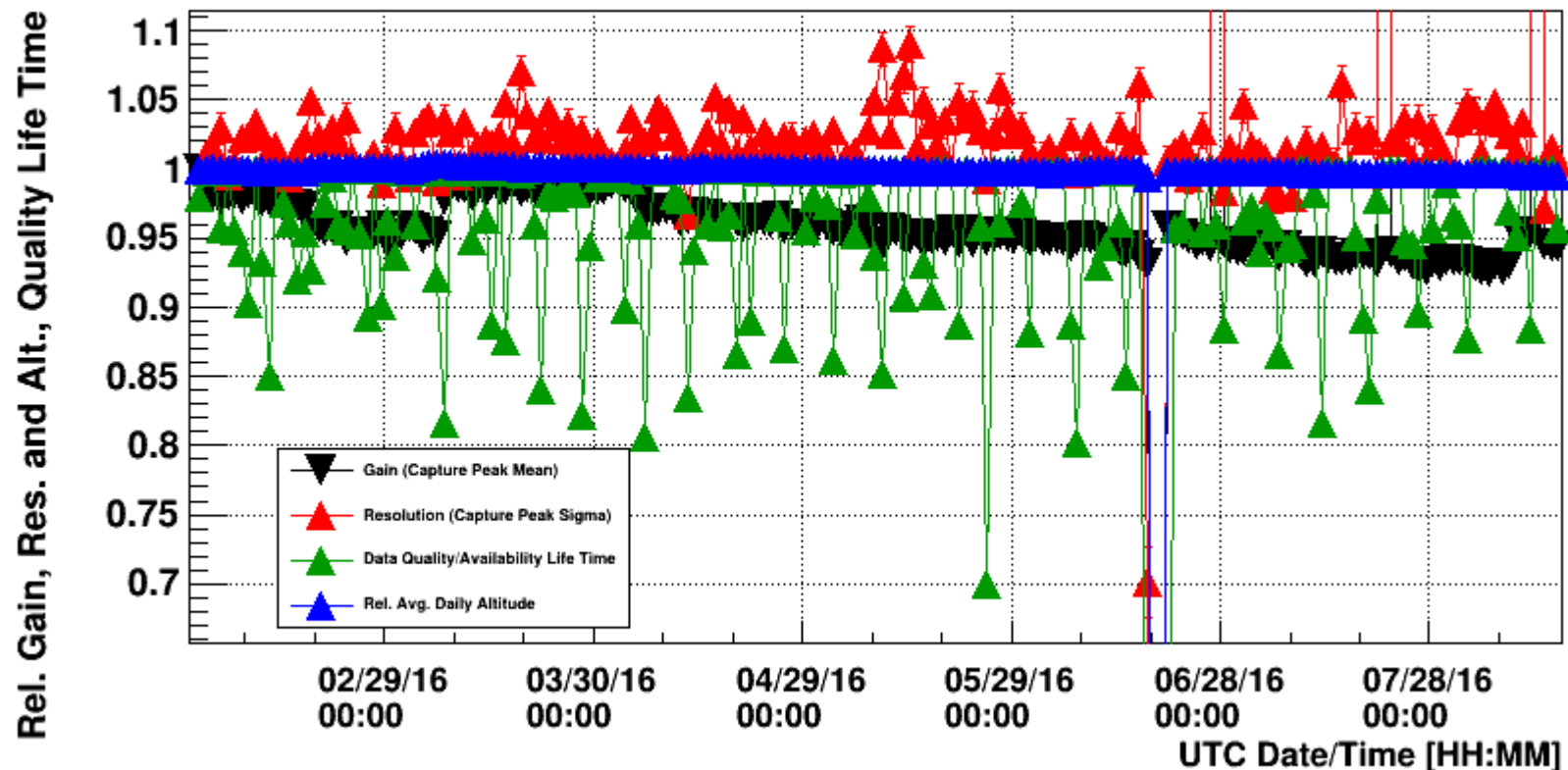
Time Delta, 2016-07-01 00:00:00 to 2016-07-02 00:00:00, Cutlevel 1



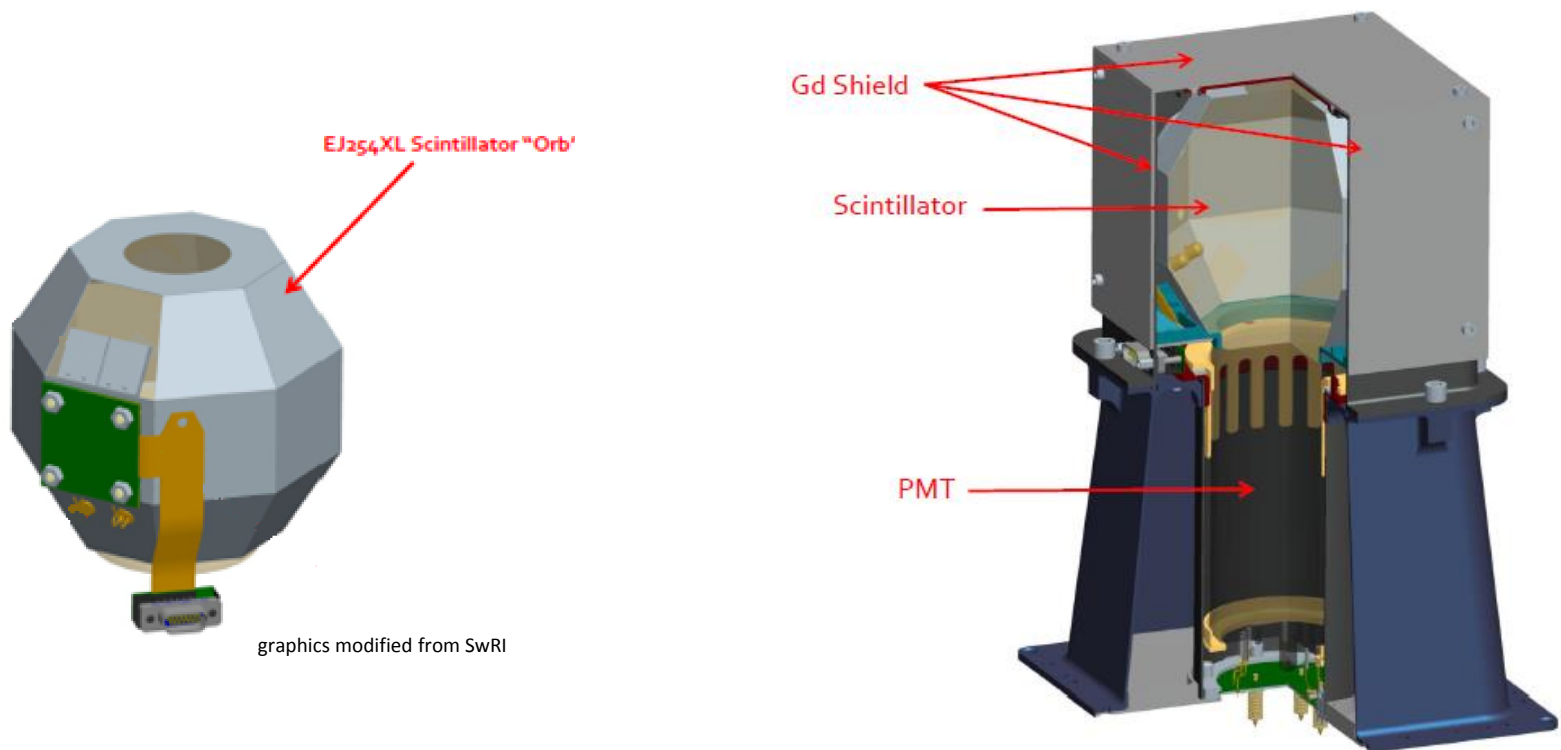
## 4. Exemplary Raw Orbit Data

- ISS altitude mostly constant/ within 1% since ACO start
- Fraction of available data >5% in about 1/3 of ACO period- correction investigations to be performed
- Rework of ground analysis software in ROOT (R. Rios) largely improved data quality and handling

History: Daily Gain, Resolution, Lifet. and Alt. Rel. to 2016-02-02, as of 2016-08-16 00:00:00



## 5. ACO Results, Status

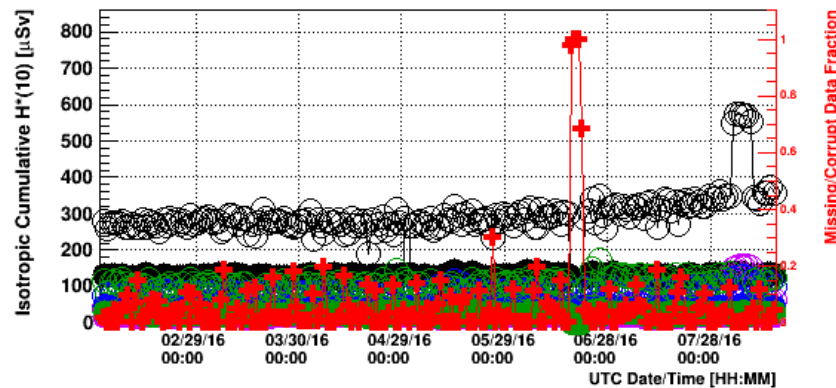




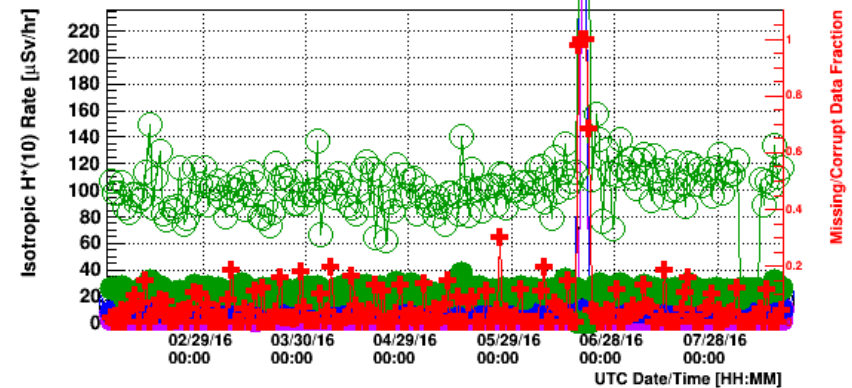
## 5. Dose Equivalent Results ACO Period, Daily Values

- Online, offline light and offline heavy: Dose equivalent results vs time, daily values

History: Daily Integral Isotropic Cumulative  $H^*(10)$  [ $\mu\text{Sv}$ ]



History: Daily Average Isotropic  $H^*(10)$  Rate [ $\mu\text{Sv/hr}$ ]

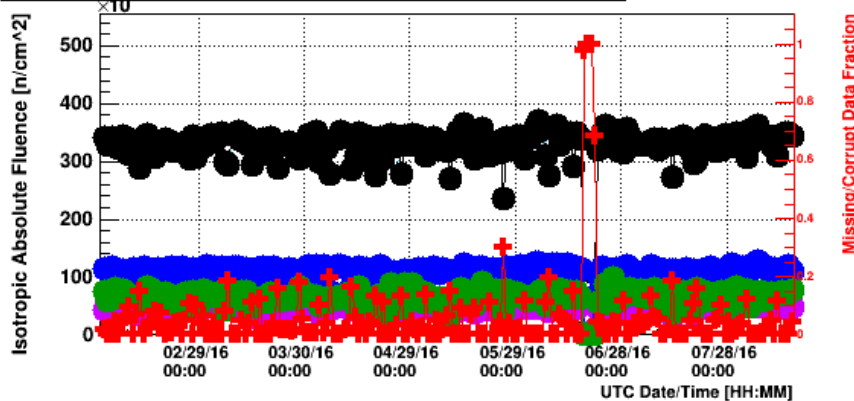


Analysis Type:

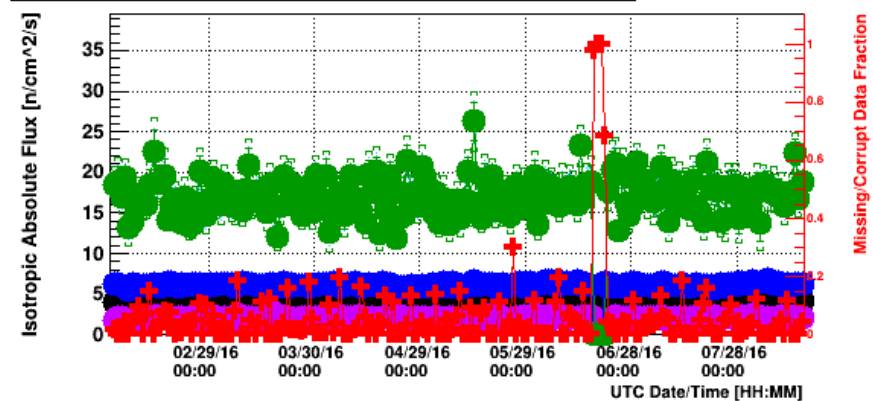
- Ground Regularized Unfolding
- On-board Cyclic Telemetered Dose Eq
- Ground Conversion

- Offline heavy: Neutron flux daily values

History: Daily Integral Isotropic Absolute Fluence [ $\text{n/cm}^2$ ]



History: Daily Average Isotropic Absolute Flux [ $\text{n/cm}^2/\text{s}$ ]



## 5. Dose Equivalent Results ACO Period Totals/Averages

- Online, offline light and offline heavy: Dose equivalent results vs time, totals and averages (overall %missing data/rejected 24 hr slices)

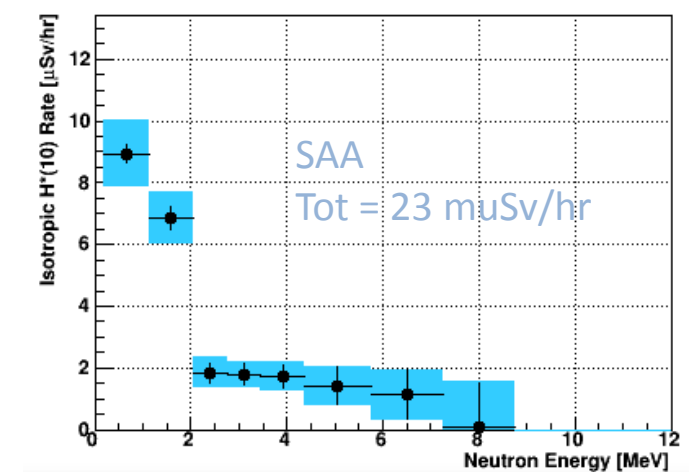
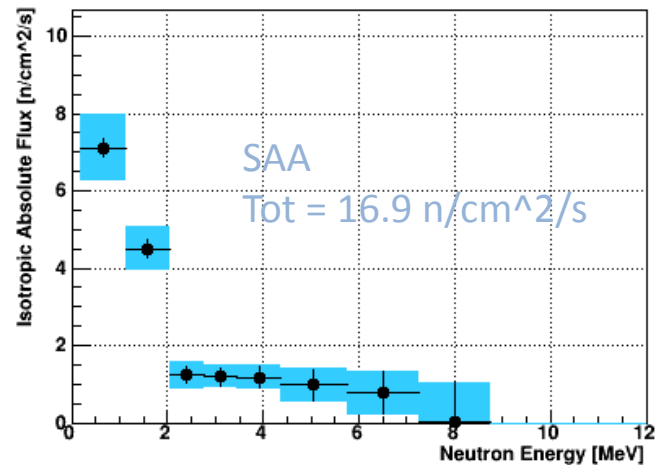
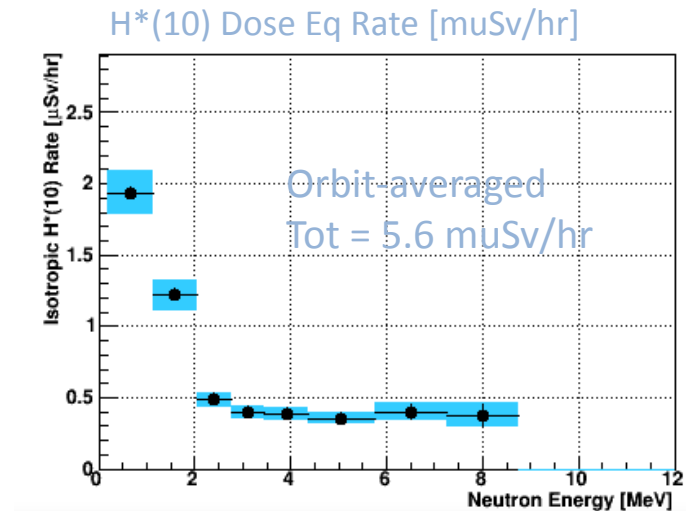
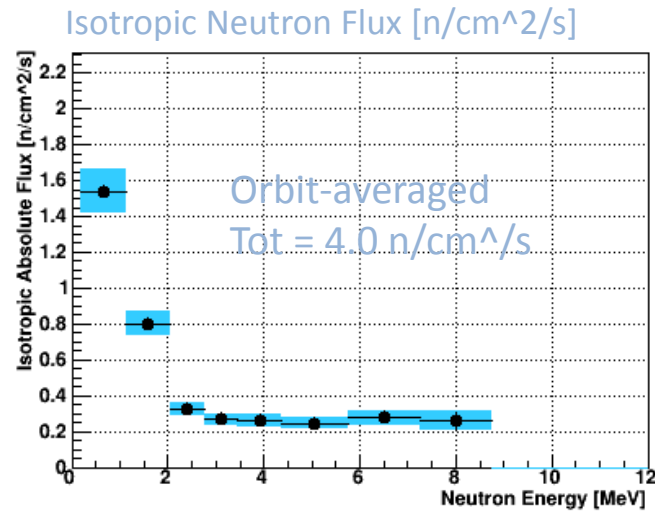
Analysis Method	Integral (orbit averaged)	Low Lat	High Lat	SAA
Online	40 mGy	11 mGy	55 mGy	67 mGy
Offline light	30 mGy	7 mGy	35 mGy	45 mGy
Offline heavy	27 mGy	6 mGy	33 mGy	41 mGy

- Offline heavy: Neutron fluence totals/averages

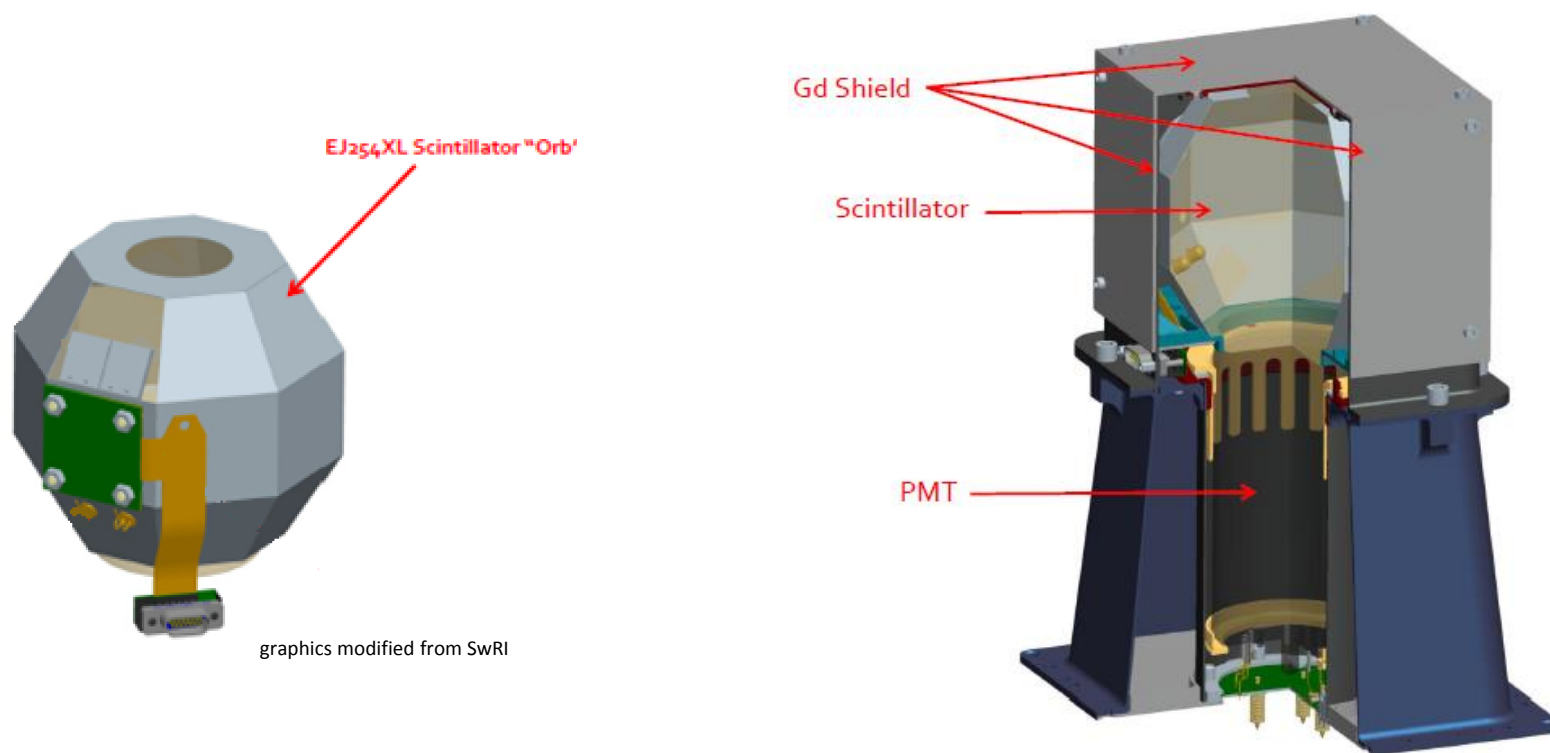
Integral (orbit averaged)	Low Lat	High Lat	SAA
3.45e+05 n/cm <sup>2</sup>	2.07e+05 n/cm <sup>2</sup>	5.78e+05 n/cm <sup>2</sup>	9.43e+05 n/cm <sup>2</sup>

## 5. Dose Equivalent Results ACO Period Totals/Averages

- Offline heavy: Neutron flux energy distributions

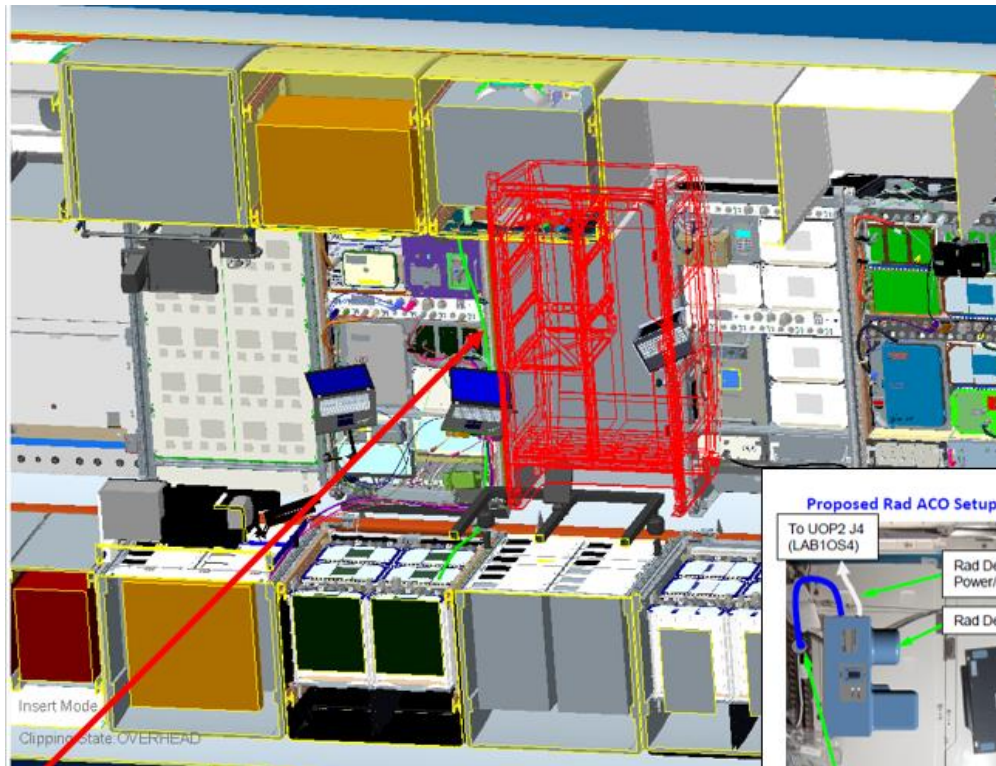


## 5.2 Comparing ACO to Simulated Data, Status

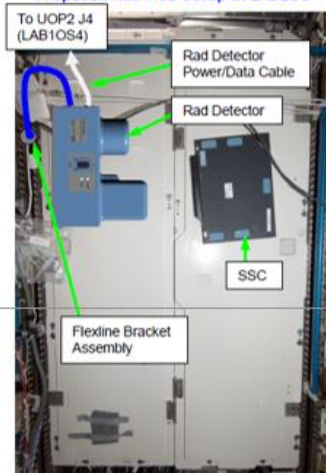


## 5.2 Dose Equivalent Results ACO Period Totals/Averages

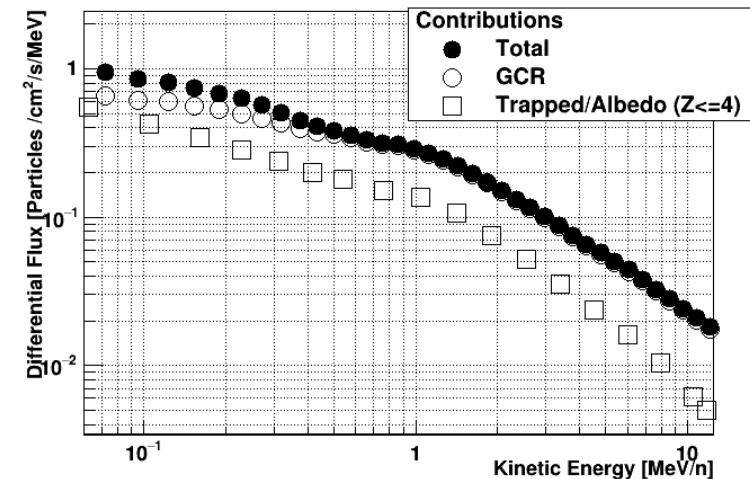
- Comparison to Oltaris (HZETRN-based) simulated data
- Ray-trace of material in US lab with latest US lab shield configuration file
- Attempt to match solar conditions: same sunspot number period matched



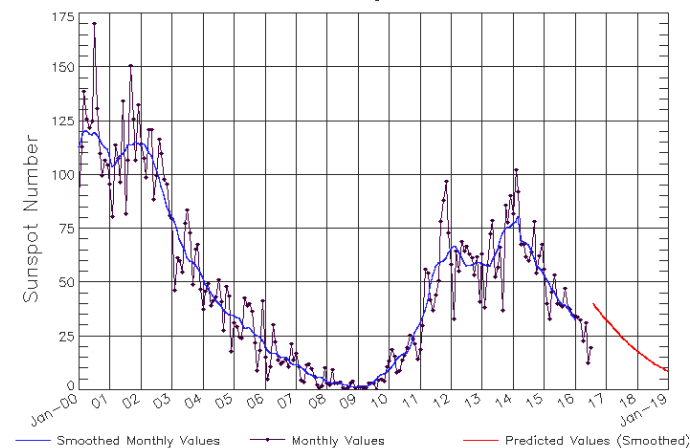
Proposed Rad ACO Setup at LAB103



Differential Particle Flux At RAD Location vs. Energy, n



ISES Solar Cycle Sunspot Number Progression  
Observed data through Jul 2016



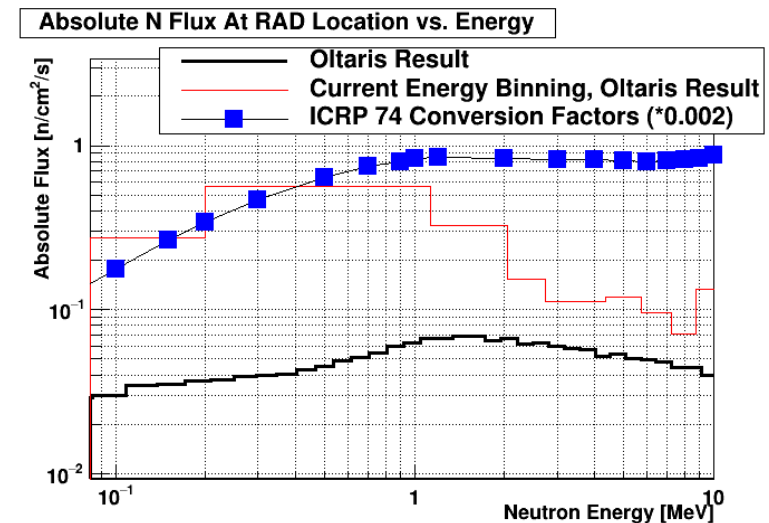
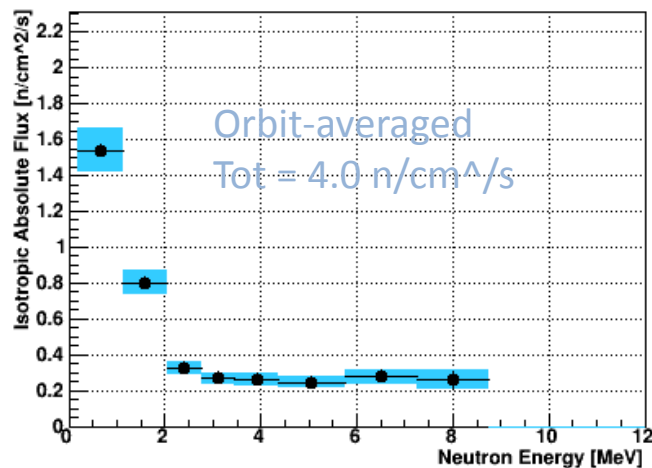
## 5.2 Dose Equivalent Results ACO Period Totals/Averages

- Comparison to Oltaris

Data Source	Integral (orbit averaged)
Online	40 mGy
Offline light	30 mGy
Offline heavy	27 mGy
Oltaris simulated	15 mGy

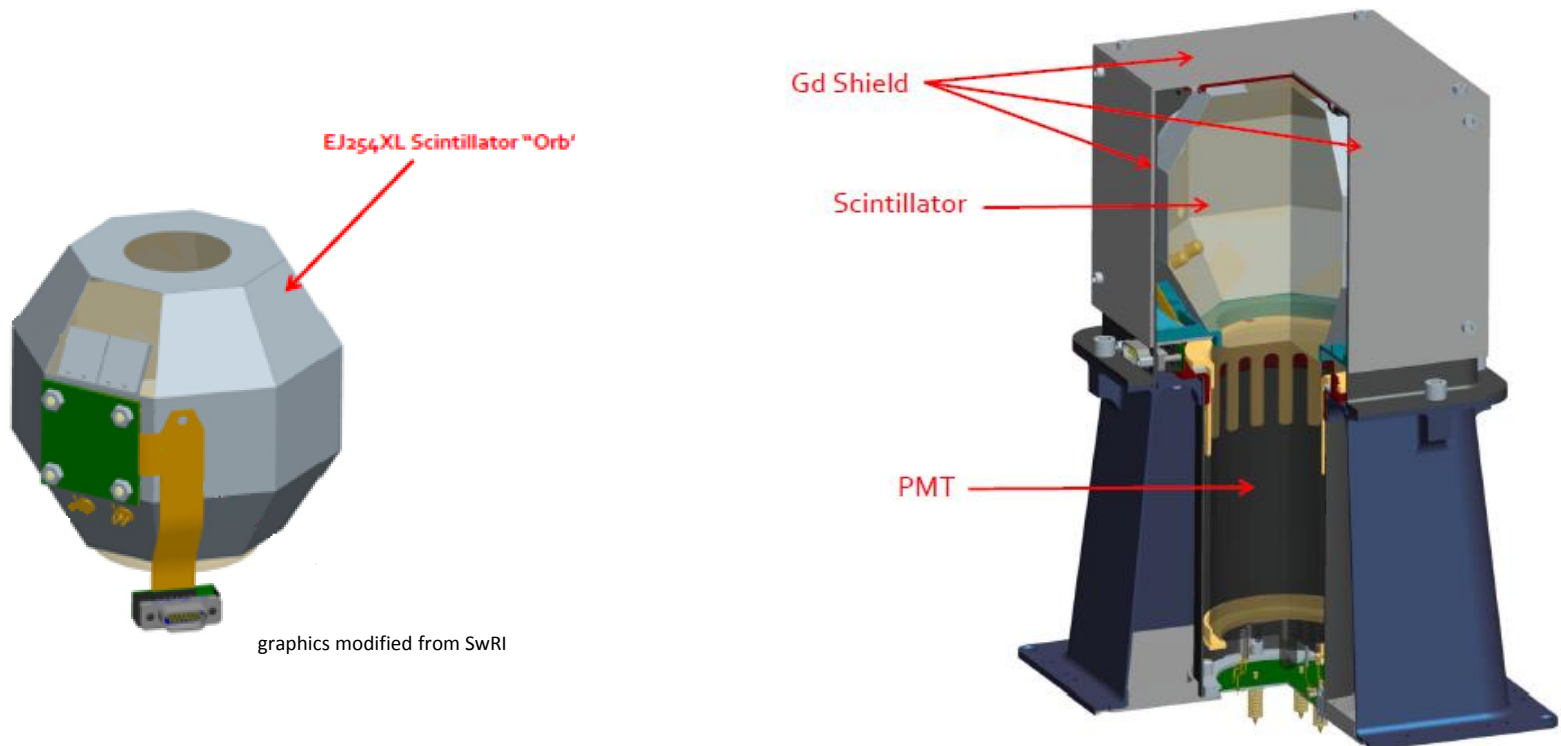
- Spectral comparison to offline heavy: Neutron fluence totals/averages

Isotropic Neutron Flux [ $\text{n}/\text{cm}^2/\text{s}$ ]



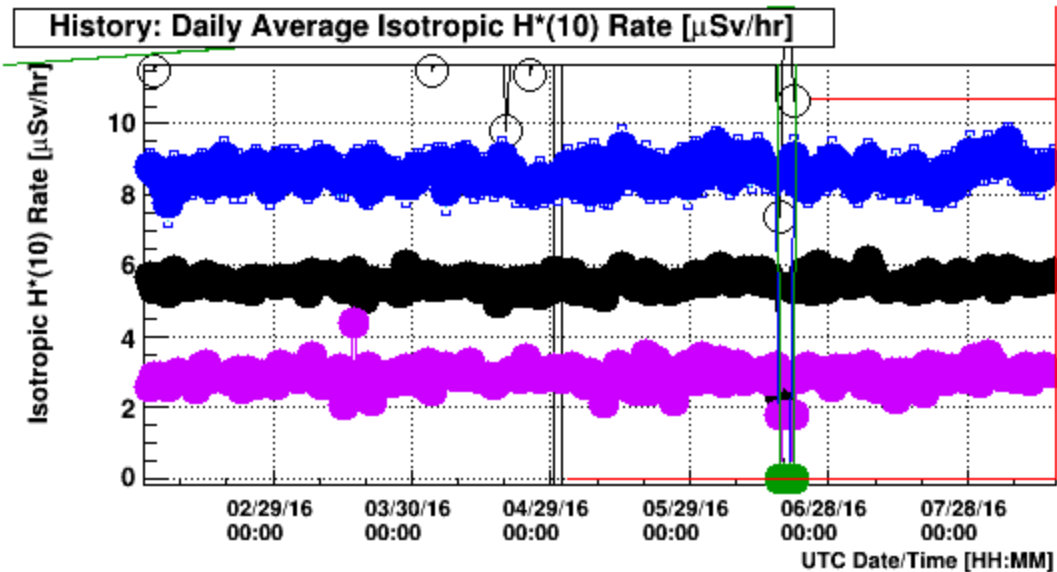


## 5.3 Comparing ACO to Other Experimental Measurements, Status

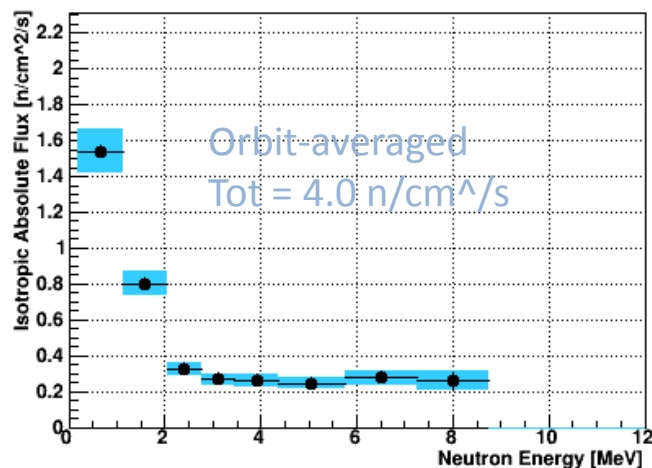


## 5.3 Dose Equivalent Results ACO Period Totals/Averages

- Previous neutron measurements: Koshiishi et al 2007 (Bonner Ball Experiments 2001)
- Bubble detectors, M. Smith et al (US lab data)
- IV-TEPC, data with LET > 15 keV/mum (neutrons + heavy ions, US Lab data)

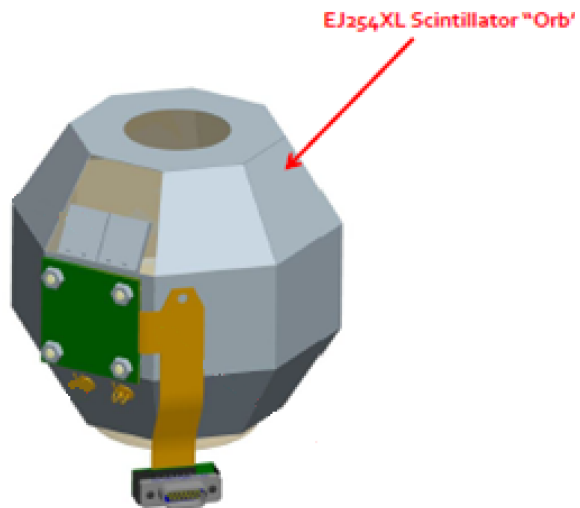


Orbit averaged

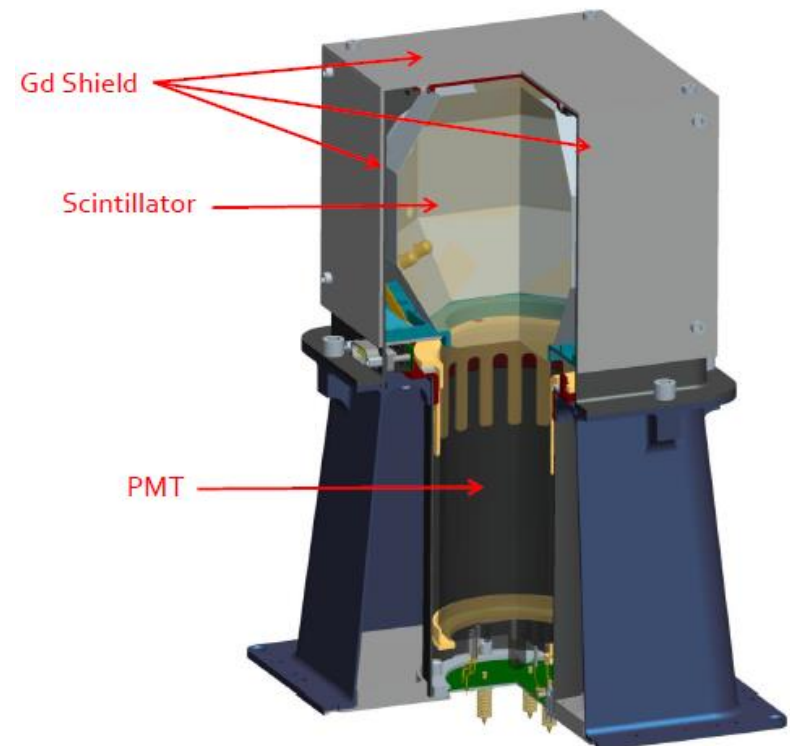


Data Source	Integral (orbit averaged)
Online	40 mGy
Offline light	30 mGy
Offline heavy	27 mGy
Oltaris simulated	15 mGy
Koshiishi et al	26 mGy
Bubble detectors	25 mGy
IV-TEPC (>15 keV/mum)	35 mGy

## 6. Forward Work



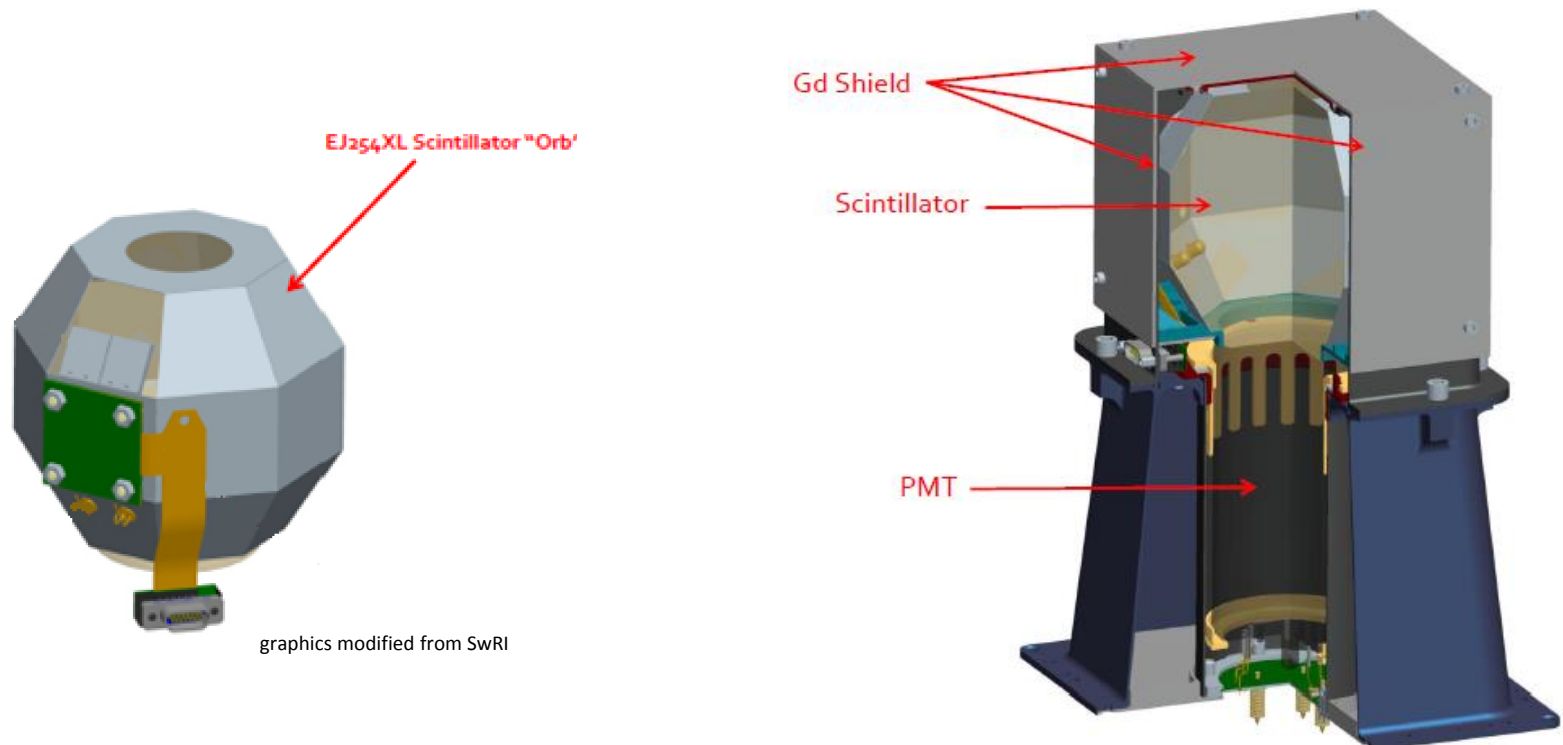
graphics modified from SwRI



## 6. Plan Ahead/Systematic Studies

- Correction for missing/corrupted data [scaling, 2D-interpolation, uncertainty (SAA)]
- Estimate sample impurities from exp data (TRIUMF) and simulation (GEANT)
- Calculate 3D efficiency from EM experimental data (PTB 2015)
- Calculate full systematic uncertainties from unfolding (boundary effects, etc.)
- Potential improvement on low energy resolution through software update (pending)

-> Publish!



# Backup

## **B: Orbital Peculiarities**

## **B: Light Calibration**



## 2. Light Function Calibration- Flowchart

- Goal: Extract continuous light function describing scintillator behavior to freely choose energy binning
- For each experimental monoenergetic data sample, start from first principles:

### a) Create energy deposit files

a.1) Generate MCNP-PoliMi energy deposits per neutron-target interaction vs. time, for experimental energies



a.2) 'Time-connect' independent MCNP source events for respective Poisson-distributed event rate

### b) Light function calibration

Create recoil spectra

b.1) Convert energy deposits to light yield with **light function**



b.2) Apply **resolution** (scintillator, PMT, pulse processing electronics)

b.3) Simulate light collection and pulse digitization in FND PMT and electronics



b.4) Convert to channelnumber values using photon calibration results

b.5) Apply FND FPGA pulse pair selection logics



Fill recoil spectrum

for each energy deposit  
(~5M per energy)

Check against experimental spectra

b.6) Apply chance coincidence subtraction, scale factor (efficiency not part of optimization, just product)



Check match to experimental data



**Adjust light function and resolution**

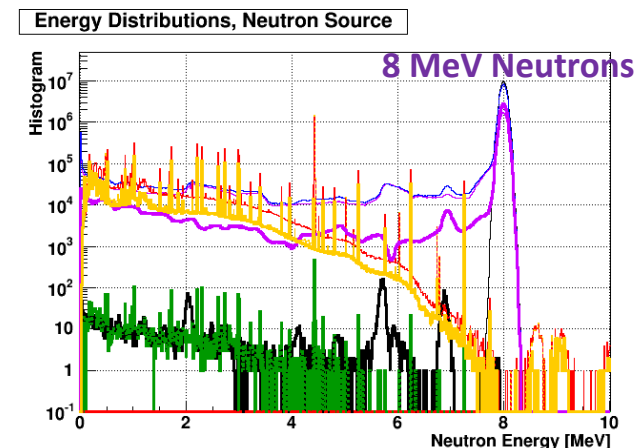
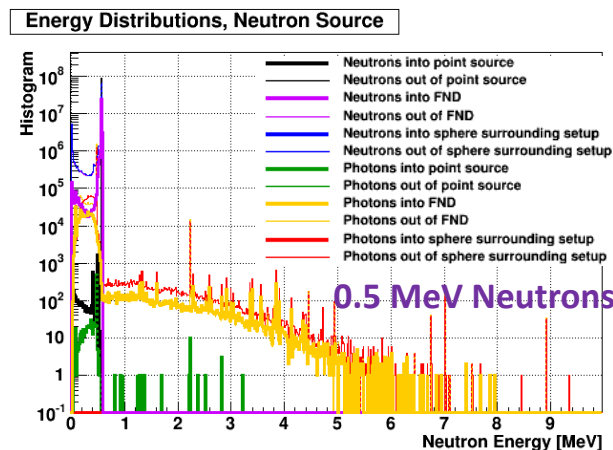
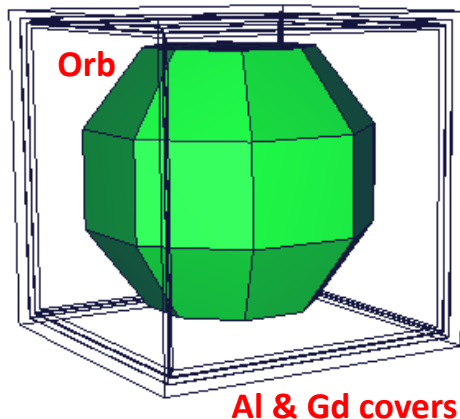
optimization loop for each energy sample

## 2.a.1 Generation of Neutron Energy Deposits: MCNP-PoliMi

- Use MCNP-**PoliMi** package:

- \* MCNP limitations for neutron propagation and fission/inelastic scattering simulation:
  - @ only returns total energy deposition of each neutron in target volume for conversion to light
  - @ photon and neutron productions in fission/inelastic collision events not correlated in time/energy/multiplicity
- \* PoliMi package writes out each interaction of single neutrons and photons
  - @ time correlation within each single history, resolution in 100 ps
  - => energy-to-light conversion possible on per-interaction-basis**
  - @ elastic, (n,gamma) and (n,n') interactions accurately modeled/propagated
- \* Generations of  $1e+08$  n per experimental energy in bias cone around FND

Model started by A. Bahadori (SRAG)



## 2.a.2 'Time-connect' Neutron Energy Deposits from MCNP-PoliMi

- Output of PoliMi: ASCII file containing interactions of neutrons and photons with target material:

History	Particle Number				Interaction		Cell	Energy Deposited [MeV]	Time [Shakes]	X-Coord.		Y-Coord.		Z-Coord.		Weight	Generation Nr		Code	Energy Prior to Collision [MeV]
	Particle Type	ZAID															Number of Scatters			
H-scatter	2805	1	1	-99	1001		10	3.589902	8.08	2.05	-1.30	-3.78	1.000E+00	0	0	0	0	0	0	4.958E+00
	2805	1	1	-99	1001		10	1.112997	8.28	0.39	0.26	-1.68	1.000E+00	0	1	0	1	0	1	1.368E+00
	2805	1	1	-99	1001		10	0.003554	8.79	2.27	2.43	0.51	1.000E+00	0	2	0	2	0	2	2.549E-01
	2805	1	1	-99	1001		10	0.181367	8.82	2.39	2.53	0.64	1.000E+00	0	3	0	3	0	3	2.514E-01
	2805	1	1	-99	6000		10	0.004136	8.82	2.39	2.53	0.65	1.000E+00	0	4	0	4	0	4	7.007E-02
B10	2805	1	1	-99	1001		10	0.043889	9.05	2.41	1.76	0.89	1.000E+00	0	5	0	5	0	5	6.590E-02
Capture!	2805	1	1	0	5010		10	2.789669	24.20	-0.40	2.31	2.63	1.000E+00	0	14	0	14	0	14	1.375E-04
Capture photon	2805	2	2	1	6		10	0.099156	24.22	-1.92	0.93	-2.22	1.000E+00	0	0	801	0	801	0	4.776E-01

- Limitation in PoliMi: no transport of non-neutron/photon decay products of capture/fission reactions -> manually distribute recoil energy among decay products & convert to light

- To create realistic succession of neutron events in scintillator: 'time-connect' PoliMi events to experimental flux (30-310 /s/cm<sup>2</sup>):

History	Particle Type			ZAID	Energy Deposited [MeV]	Absolute Time [μs]
	Interaction					
15	1	-99	6000	0.3258	200.9430278347747105272	
15	1	-1	6000	1.223006	200.9446278347747067983	
15	1	-99	1001	1.19312	200.9471278347747045245	
20	1	-1	6000	1.153536	249.6897651601931613641	
21	1	-99	6000	2.070328	258.0006369570315882811	
35	1	-99	6000	0.027568	372.9355042009522662738	
...						
99999932	1	-99	6000	0.009083	943205800.4175952672958	
99999958	1	-99	1001	1.209701	943206036.2944241762161	
99999988	1	-1	6000	0.332827	943206258.0235788822174	
99999988	1	-99	1001	0.772745	943206258.0235788822174	
99999997	1	-99	1001	1.429591	943206423.4481251239777	

→ ~15 min

## 2.b.1 Convert Energy Deposit to Light- Function Parameterization

- Fit to Verbinski data parameterized as: 2<sup>nd</sup> order polynomial at low deposited energy;  
sqrt(const+E<sup>2</sup>) at high energy
- Change 5 parameters to optimize match with experimental data

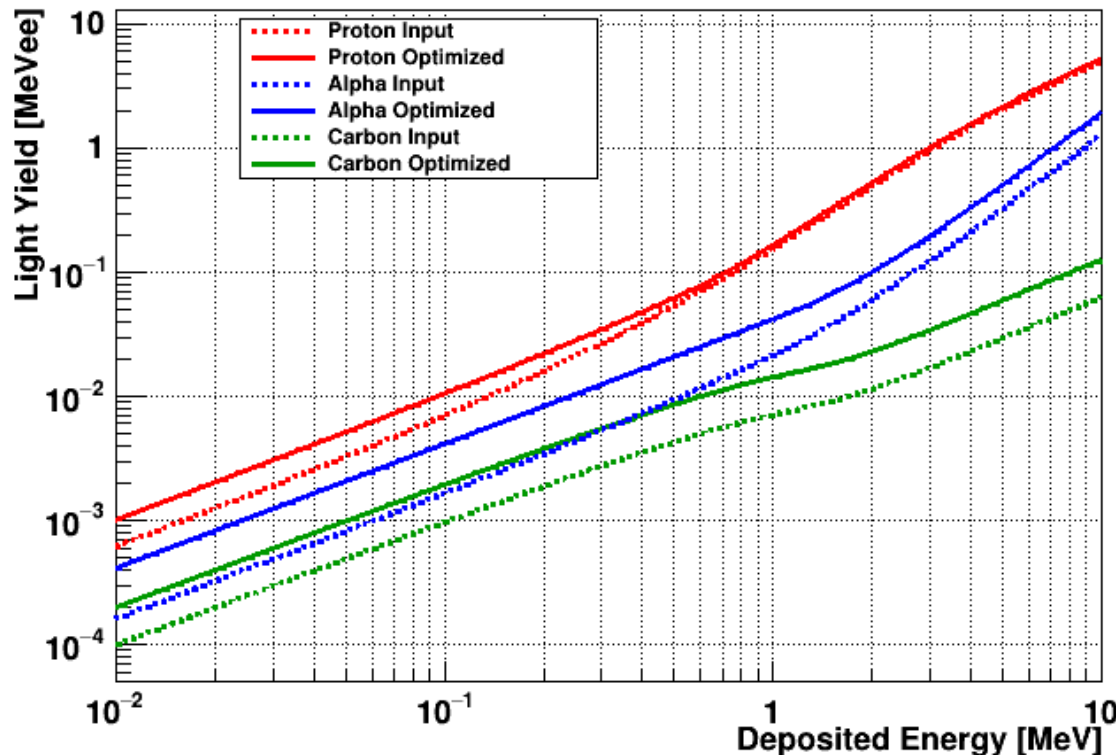
$$L(x_{ED}) = \begin{cases} ax_{ED} + bx_{ED}^2 & \text{for } x < g \\ c + d\sqrt{e^2 + f^2 x_{ED}^2} & \text{for } x \geq g, \text{ where} \end{cases}$$

$$a = \frac{df^2 g}{\sqrt{e^2 + f^2 g^2}} - 2bg$$

$$c = ag + bg^2 - d\sqrt{e^2 + f^2 g^2}$$

Continuity requirements for 1<sup>st</sup> and 2<sup>nd</sup> derivative

Neutron Light Conversion Functions

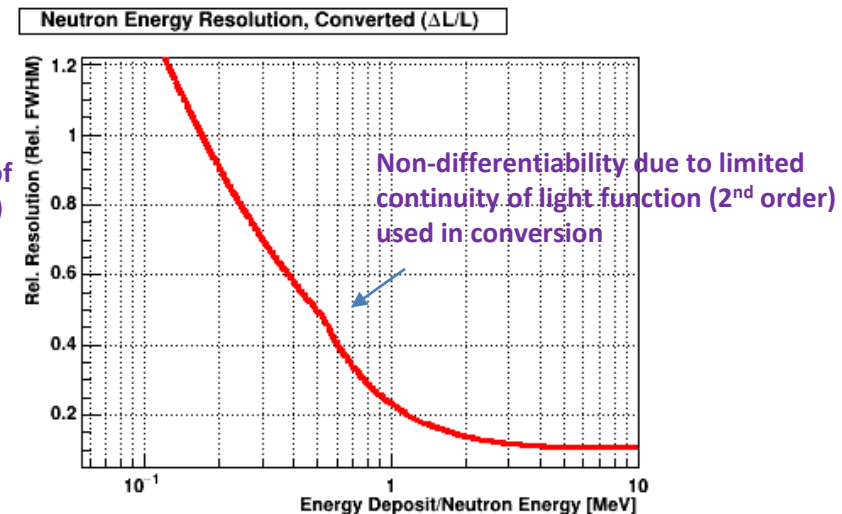
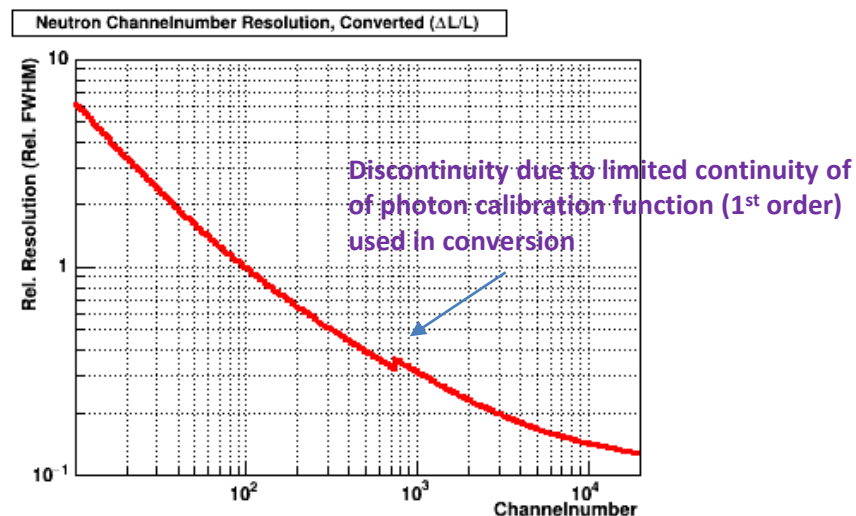
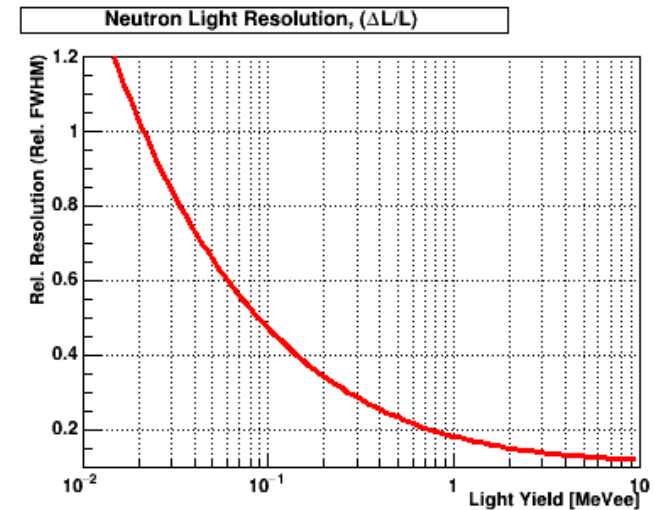


## 2.b.2 Apply Resolution- Implementation

- Single-point implementation of all experimental resolution contributions:
  - \* light production/quenching/reflections in plastic,
  - \* light coupling scintillator to PMT
  - \* PMT photon detection
  - \* electronic noise (PMT/amplifier) etc
- Optimize 3 parameters to match experimental data

$\Delta L / L$  (rel. FWHM):

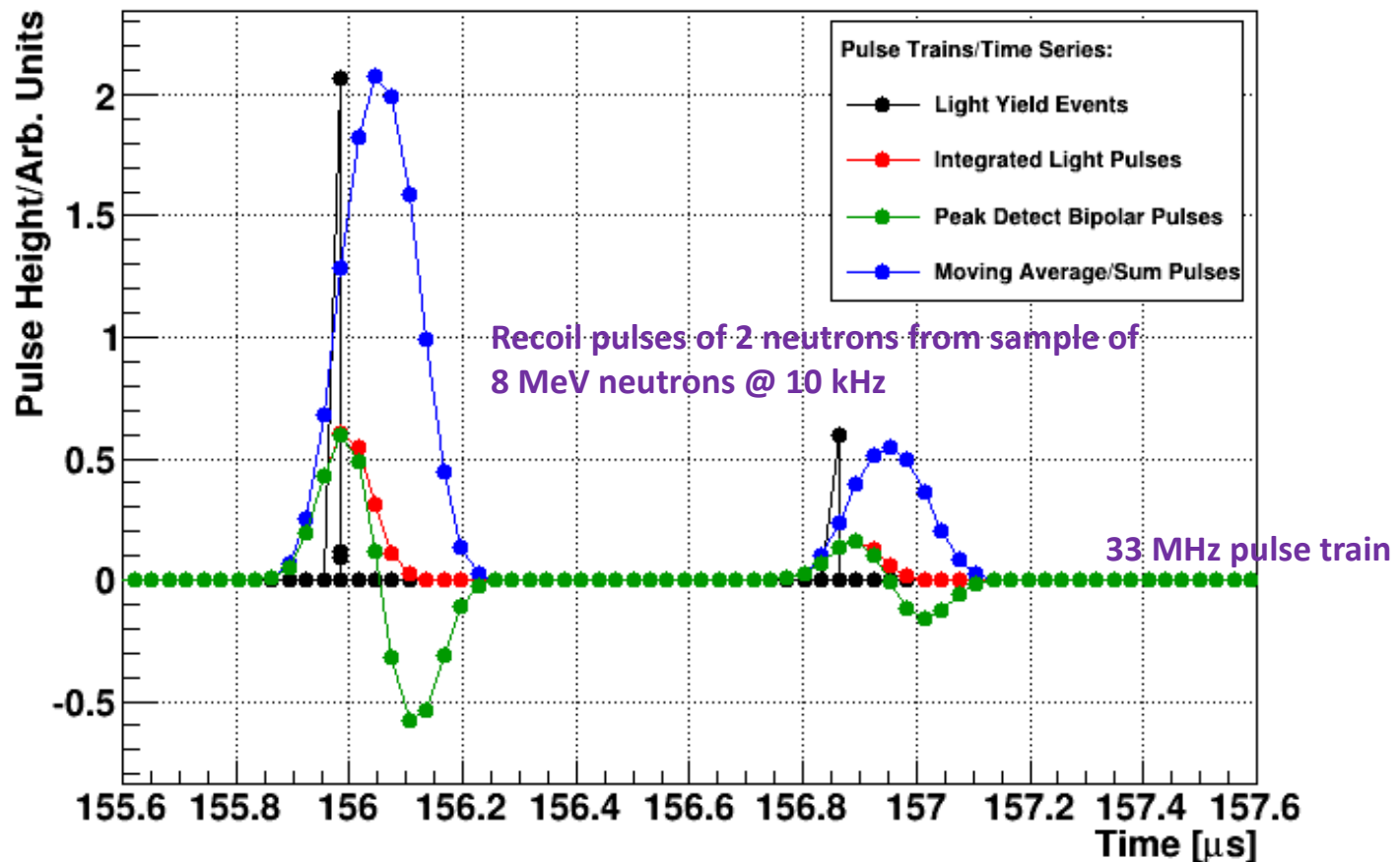
$$\frac{\Delta L}{L} = \left( \alpha^2 + \frac{\beta^2}{L} + \frac{\gamma^2}{L^2} \right)^{1/2}$$



## 2.b.3 Light Collection/Pulse Digitization (see Michael V's talk)

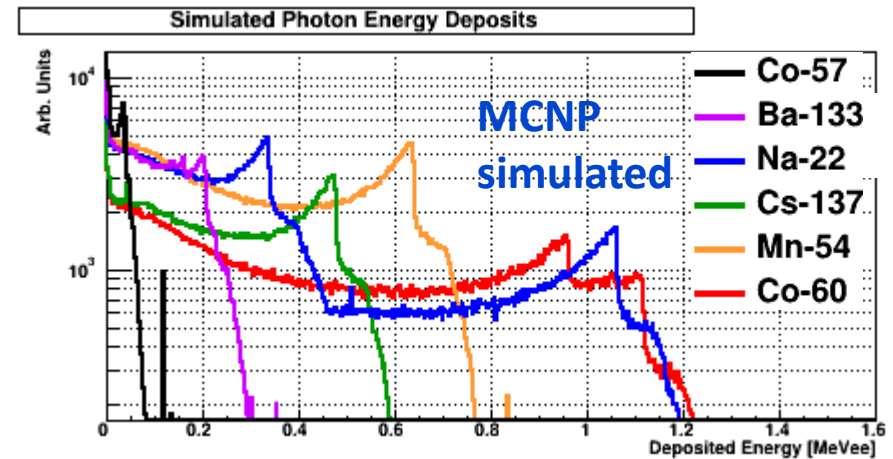
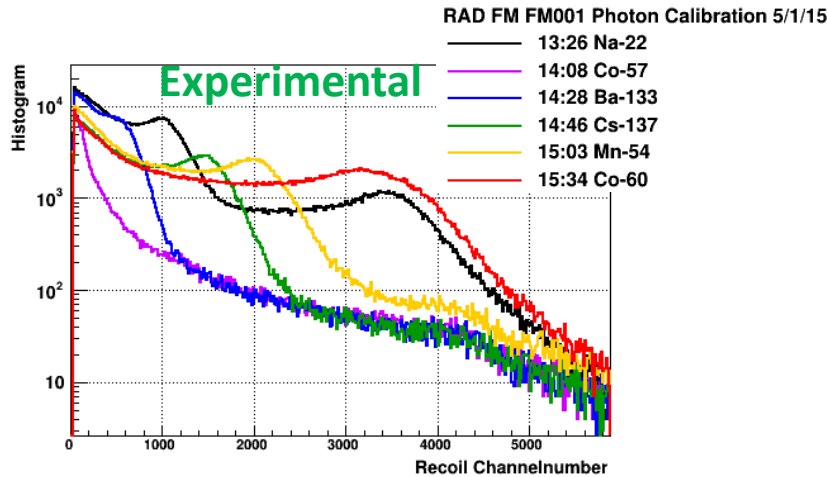
- Convert light yields to corresponding **electronics signal pulses** via Gaussian function sampled by 33 MHz clock; area normalized to light yield
- Two filters create **bipolar signals** for peak detection and '**moving average (sum)**' for signal height
- Time width of Gaussian chosen to match experimental signal processing pulse width (full width ~390 ns)

Pulse Processing Time Series



## 2.b.4 Light to Channelnumber Conversion: Photon Calibration

- Inputs: experimental photon source and MCNP-simulated energy deposit spectra
- Perform global fit of conversion function parameters: create channelnumber spectra from generated deposited energy spectra



$$N_{\text{Exp. Gamma}}(x_{\text{CHN}}) = N_{\text{Exp. Bg}}(x_{\text{CHN}}) + \int R(x_{\text{CHN}}, x_{\text{ED}}) N_{\text{Sim. MC}}(x_{\text{ED}}) dx_{\text{ED}}$$

$$R(x_{\text{CHN}}, x_{\text{ED}}) = e^{-\frac{(ED(x_{\text{CHN}}) - x_{\text{ED}})^2}{2\sigma^2}}$$

Channelnumber-to-light yield conversion:

$$ED(x_{\text{CHN}}) = \begin{cases} a + bx_{\text{CHN}}^c & \text{for } x < e \\ d + bx_{\text{CHN}} & \text{for } x \geq e, \text{ where } d = a + be^c - be \end{cases}$$

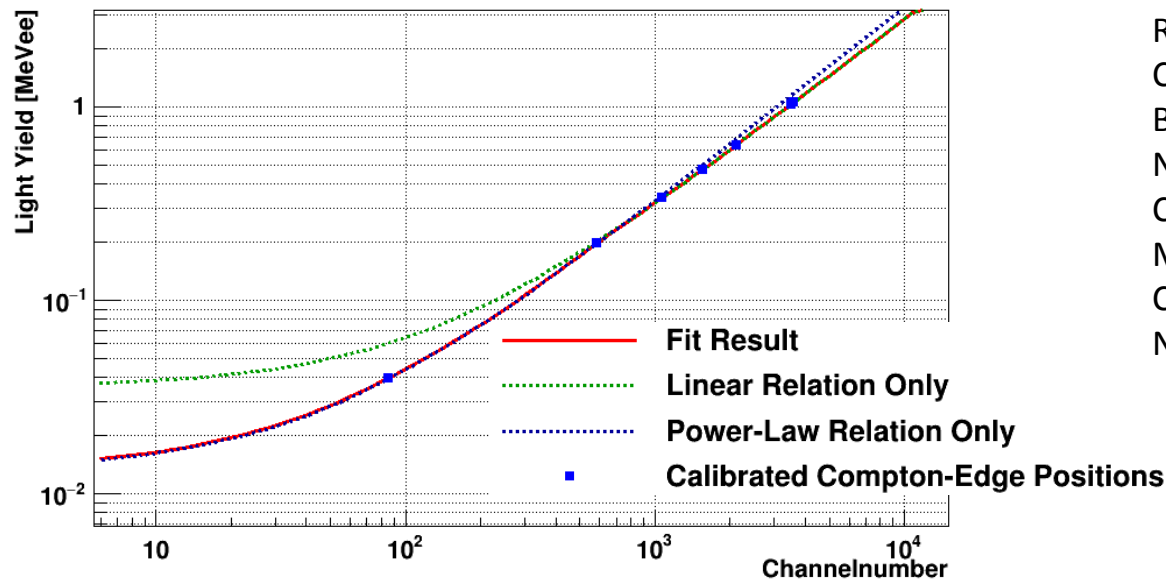
Continuity requirement



## 2.b.4 Light to Channelnumber Conversion: Photon Calibration

- Result: Low light yield region prefers nonlinear (power law) shape (also seen in other literature):

FND Channelnumber to Light Yield Conversion



Global red. chisq. =  $695 / 490 = 1.42$

Red. chisq. for single plots:

Co-57:  $27 / 31 = 0.86$

Ba-133:  $63 / 35 = 1.80$

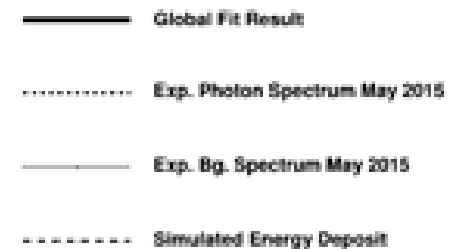
Na-22 a):  $53 / 32 = 1.67$

Cs-137:  $108 / 70 = 1.54$

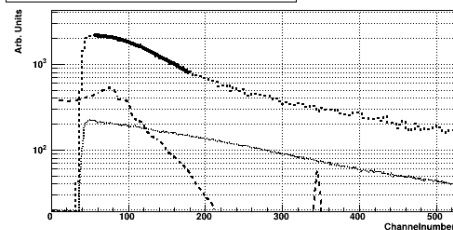
Mn-54:  $69 / 80 = 0.86$

Co-60:  $211 / 160 = 1.32$

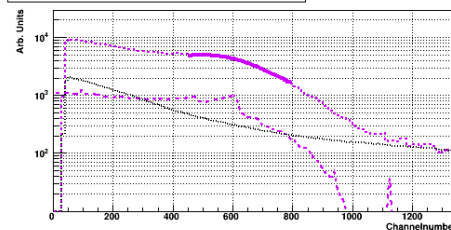
Na-22 b):  $164 / 100 = 1.64$



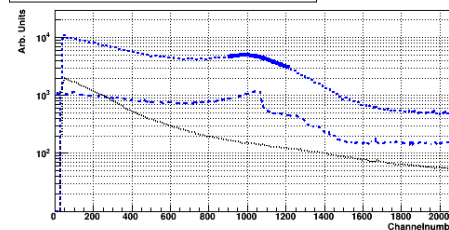
Exp. FND Photon Spectrum 0, Co-57



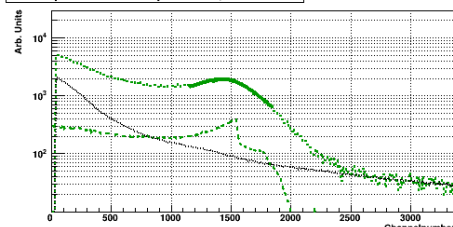
Exp. FND Photon Spectrum 1, Ba-133



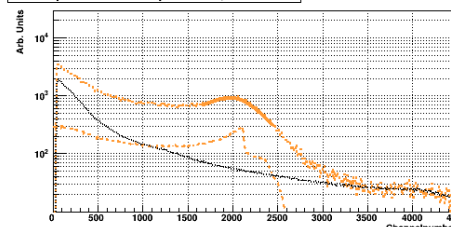
Exp. FND Photon Spectrum 2, Na-22 a)



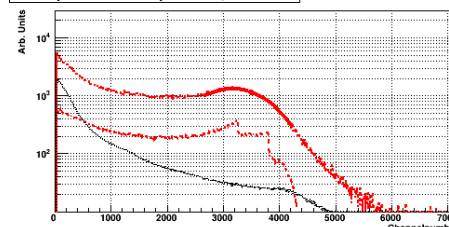
Exp. FND Photon Spectrum 3, Cs-137



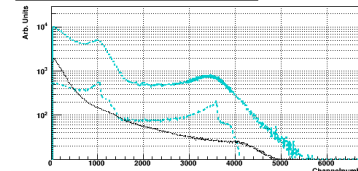
Exp. FND Photon Spectrum 4, Mn-54



Exp. FND Photon Spectrum 5, Co-60

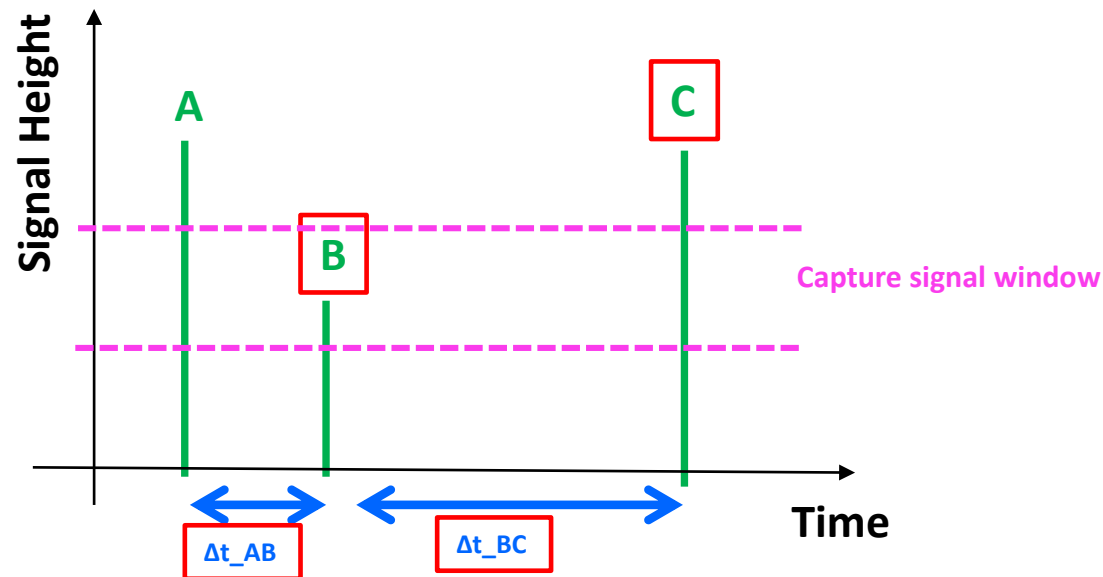


Exp. FND Photon Spectrum 6, Na-22 b)



## 2.b.5 FND Pulse Pair Selection (see Michael V's talk)

- Apply same selection as FND FPGA
- Algorithm considers three latest detected pulse amplitudes (moving averages) and time intervals between them (zero crossing of bipolar signal)



- **Pulse selection logics:** accept A, B as pulse pair:

I)  $SH\_B$  in capture signal window &&

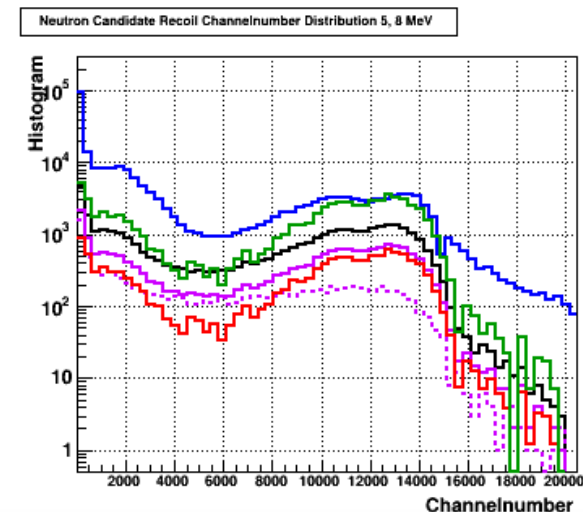
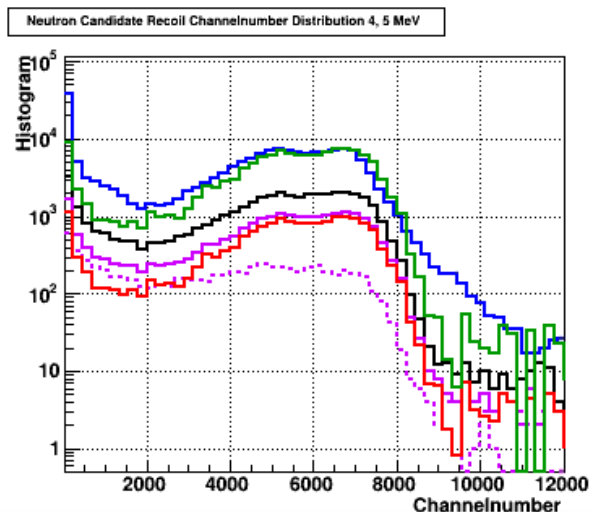
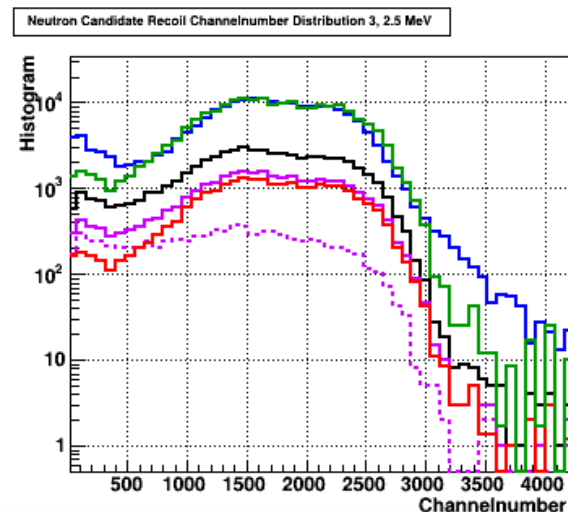
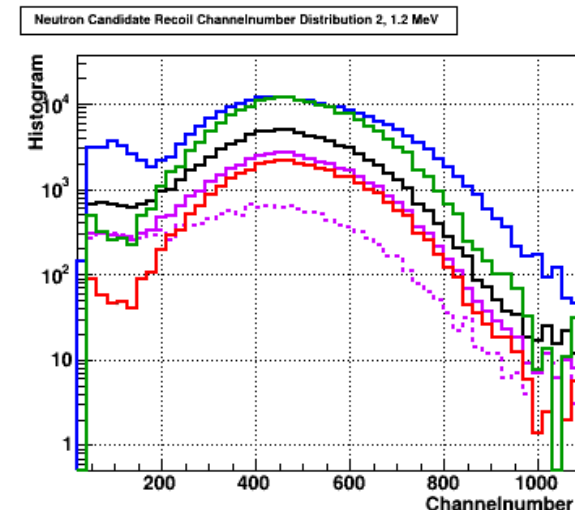
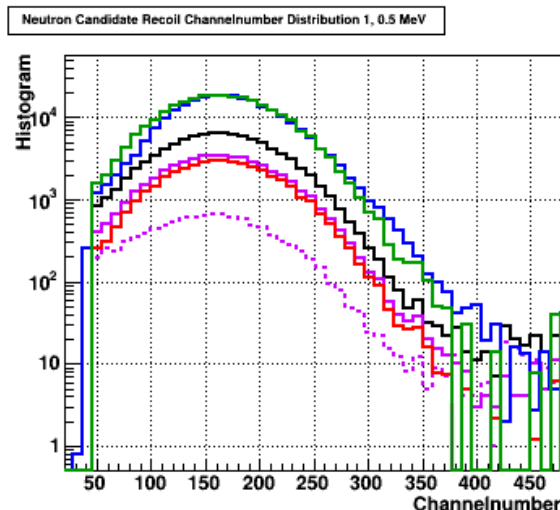
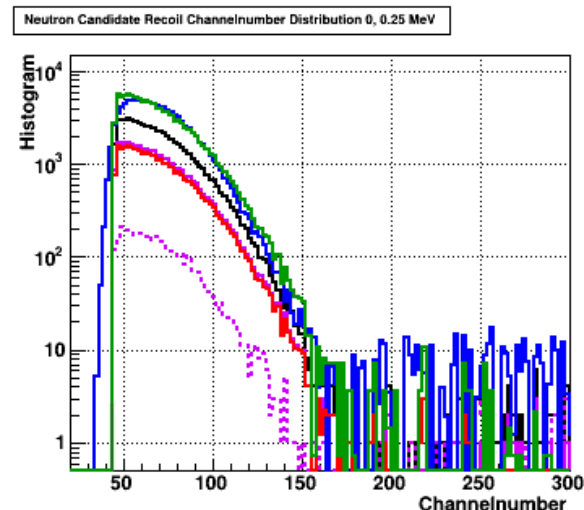
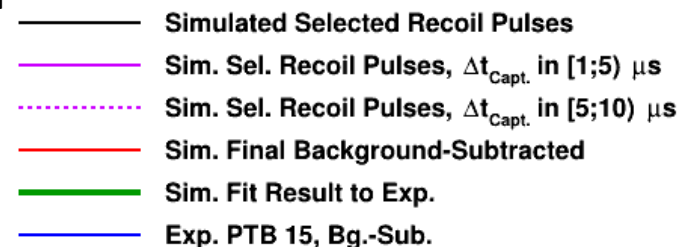
II)  $\Delta t_{AB}$  in capture time window &&

III)  $\Delta t_{AB} < \Delta t_{BC}$  ||

( $SH\_C$  outside of capture signal window ||  $\Delta t_{BC}$  outside of capture time window )

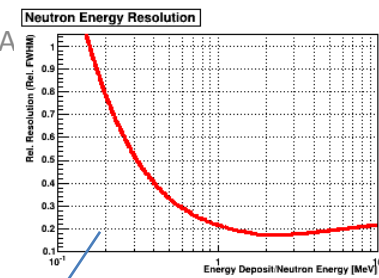
## 2. Preliminary Calibration Results- Recoil Spectra Match

- Deviations for low channelnumbers at mid to high energies: further analysis to be done to identify missing process/incorrect treatment of neutron interactions; resolution to be adjusted as well



## **B: Isotropic Source Term Correction**

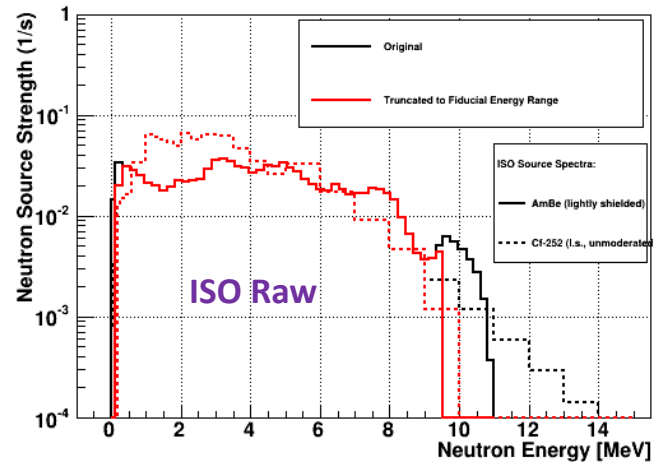
## **B: Offline Light Spectrum Extraction Study**



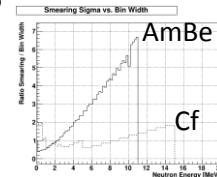
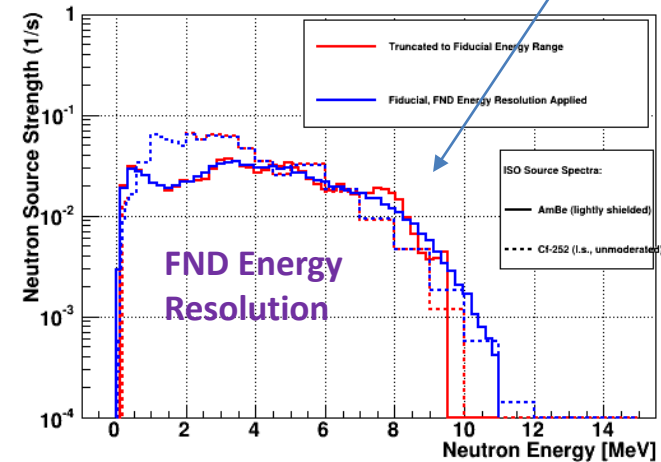
## 2c) Direct Mapping/Conversion Spectral Match Test

- Created 'truth' distributions from ISO for AmBe and Cf sources: apply detector resolution, direct mapping binning and energy range selection (0.5-8 MeV)
- \* Cf ISO binning mostly too wide for smearing to have effect;

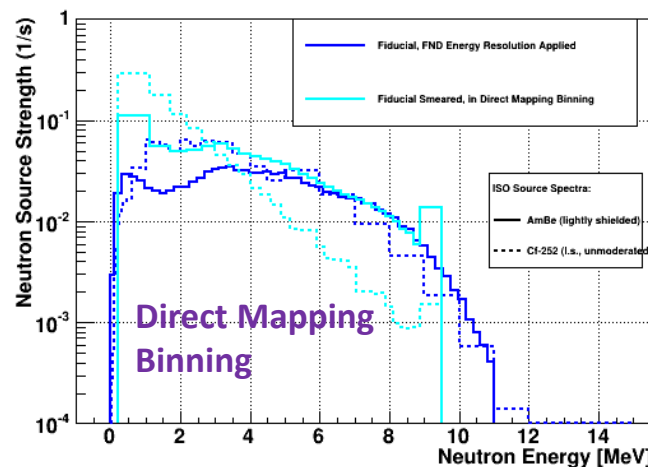
ISO AmBe and Cf Neutron Spectra, Binnings & FND Resolution



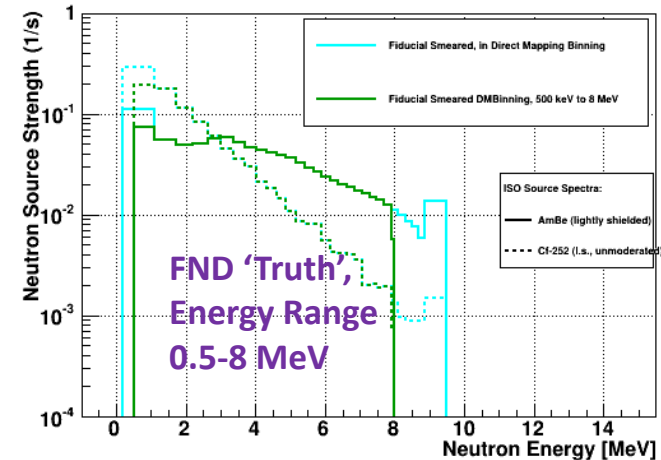
ISO AmBe and Cf Neutron Spectra, Binnings & FND Resolution



ISO AmBe and Cf Neutron Spectra, Binnings & FND Resolution



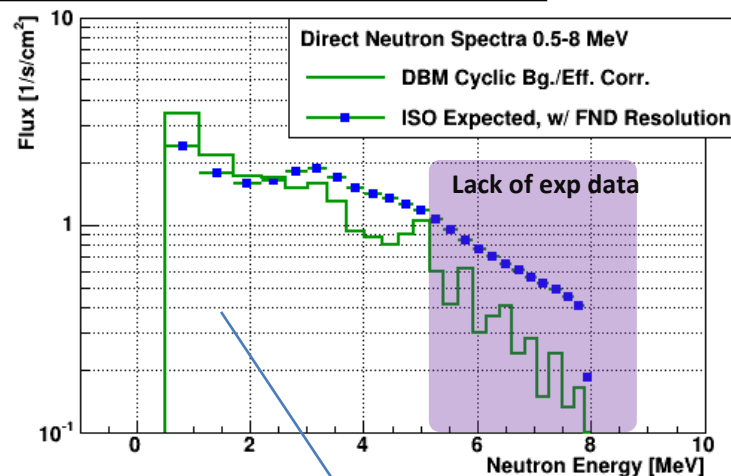
ISO AmBe and Cf Neutron Spectra, Binnings & FND Resolution



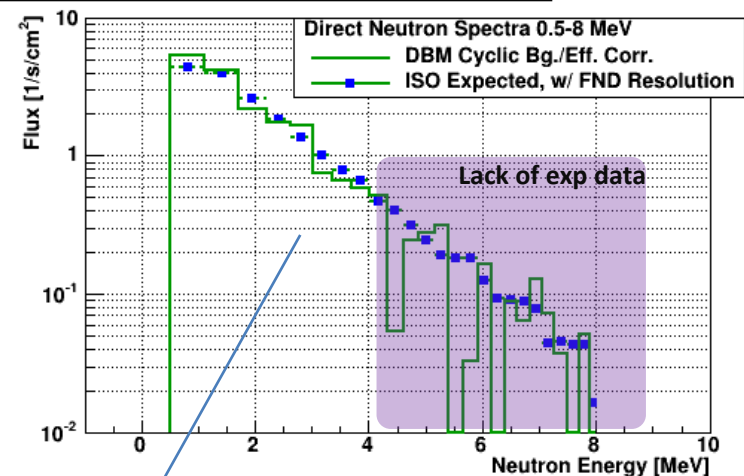
## 2c) Direct Mapping/Conversion Spectral Match Test

- Scale 'truth' histograms with PTB reported (adjusted) neutron flux
- Comparison with GAS analysis results statistics-limited to  $< \sim 5$  MeV (only spotty shadow cone and background subtraction data at higher chn bins):
- @ Expected: Low energy spectrum overestimated, medium/high energy spectrum underestimated
- @ AmBe spectrum shows structure in ISO-truth, not reflected in DBM spectrum: deviations +45% to -41%;
- @ Cf spectrum closer (statistics limited): overestimate at low bins  $\sim 22\%$ , medium energy bins large uncertainties, in part consistent;
- **Conclusion: Direct Mapping/Conversion analysis method by design shows limitations in reproducing neutron energy spectra.**

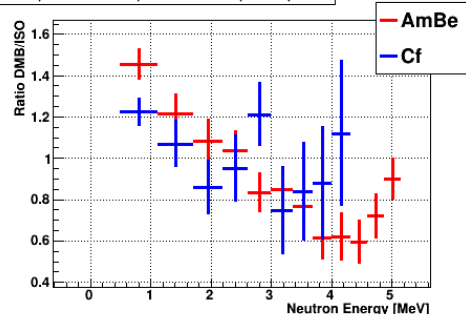
AmBe DMB Direct PTB Experimental and Expected (ISO) Neutron Spectra



Cf DMB Direct PTB Experimental and Expected (ISO) Neutron Spectra



Ratio Experimental DMB Spectra over ISO Expected Spectra





## **B: MCNP Neutron Cross Sections**

## 4.1a Simulation of Neutron Energy Deposits: MCNP-PoliMi

- for all materials use ENDF-VII library at 300 K, assembled in 2005; max energy 20 MeV, 500-3500 energies depending on material

<span style="color: red;">—</span>	<span style="border: 1px solid black; padding: 2px;">red ▼</span>	pendfb7/B10:1	5-B - 10 LANL EVAL-APR06 G.M.Hale,P.G.Young	total
<span style="color: green;">—</span>	<span style="border: 1px solid black; padding: 2px;">green ▼</span>	pendfb7/B10:2	5-B - 10 LANL EVAL-APR06 G.M.Hale,P.G.Young	elastic
<span style="color: blue;">—</span>	<span style="border: 1px solid black; padding: 2px;">blue ▼</span>	pendfb7/B10:4	5-B - 10 LANL EVAL-APR06 G.M.Hale,P.G.Young	production of one n in exit channel
<span style="color: purple;">—</span>	<span style="border: 1px solid black; padding: 2px;">purple ▼</span>	pendfb7/B10:102	5-B - 10 LANL EVAL-APR06 G.M.Hale,P.G.Young	radiative capture
<span style="color: lime;">—</span>	<span style="border: 1px solid black; padding: 2px;">Lgreen ▼</span>	pendfb7/B10:107	5-B - 10 LANL EVAL-APR06 G.M.Hale,P.G.Young	production of one alpha particle + residual

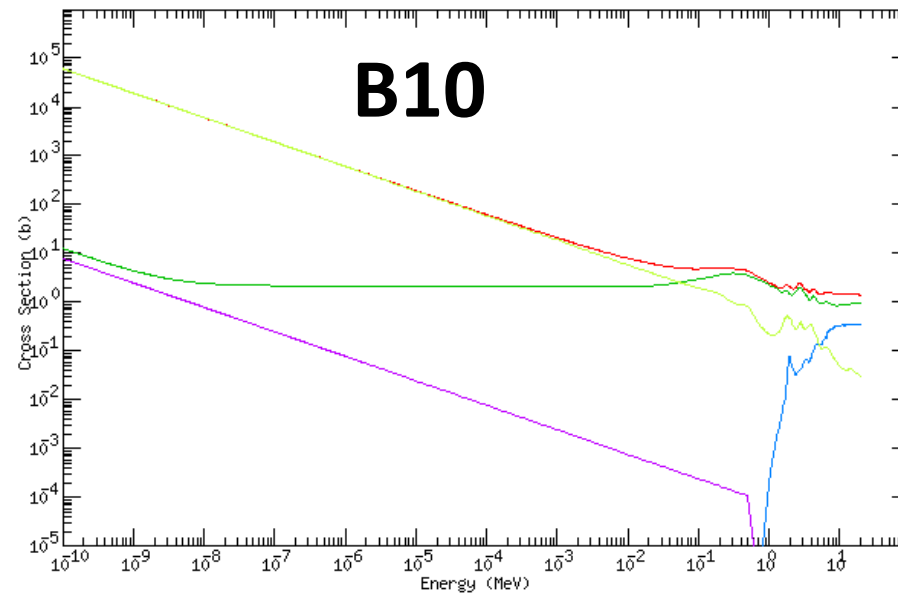
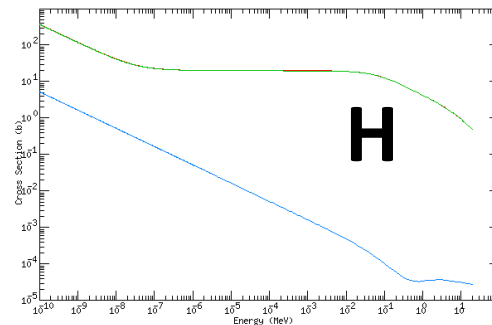
Get [Text Data](#) with right mouse click. (Please be patient.)

Get [EPS](#)

<span style="color: red;">—</span>	<span style="border: 1px solid black; padding: 2px;">red ▼</span>	pendfb7/H1:1	1-H - 1 LANL EVAL-OCT05 G.M.Hale
<span style="color: green;">—</span>	<span style="border: 1px solid black; padding: 2px;">green ▼</span>	pendfb7/H1:2	1-H - 1 LANL EVAL-OCT05 G.M.Hale
<span style="color: blue;">—</span>	<span style="border: 1px solid black; padding: 2px;">blue ▼</span>	pendfb7/H1:102	1-H - 1 LANL EVAL-OCT05 G.M.Hale

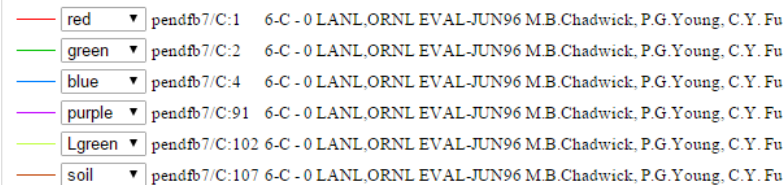
Get [Text Data](#) with right mouse click. (Please be patient.)

Get [EPS](#)



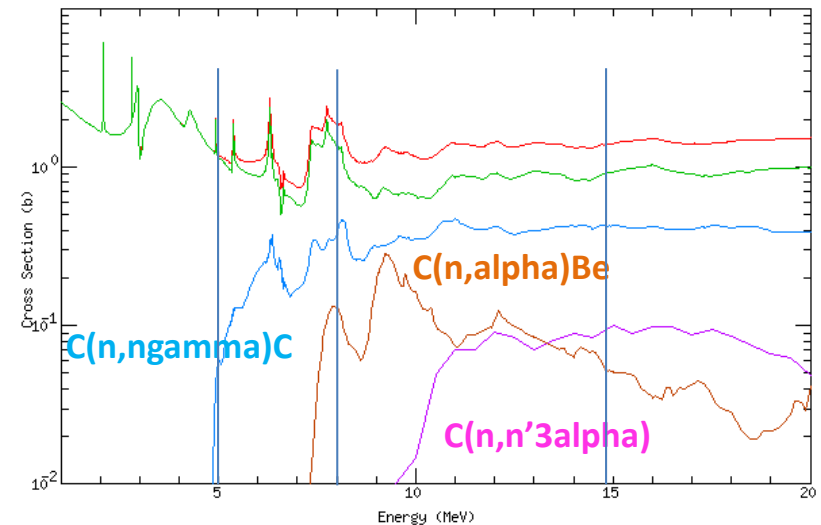
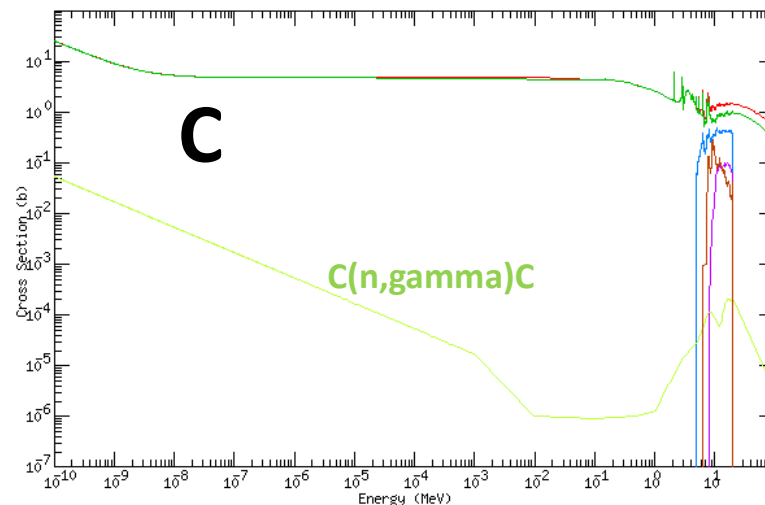
## 4.1a Simulation of Neutron Energy Deposits: MCNP-PoliMi

- for all materials use ENDF-VII library at 300 K, assembled in 2005; max energy 20 MeV, 500-3500 energies depending on material



Get [Text Data](#) with right mouse click. (Please be patient.)

Get [EPS](#)



## **B: Photon Calibration Nonlinearities**

## 6) Low Energy Nonlinear Light Output in Literature

Energy deposit -> Light Yield -> Channelnumber

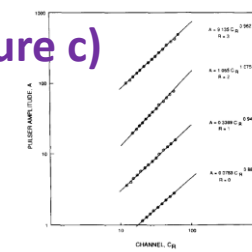
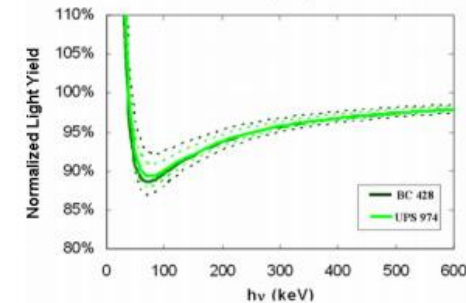
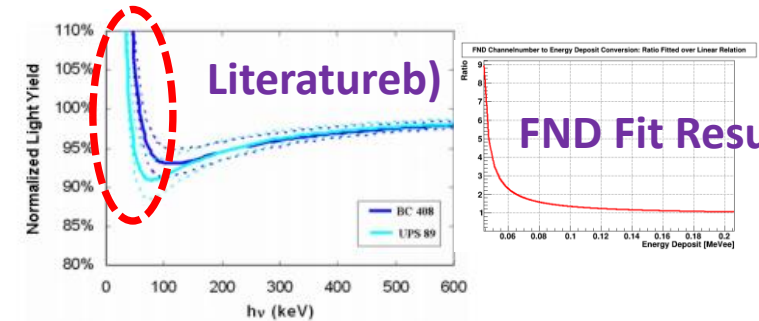
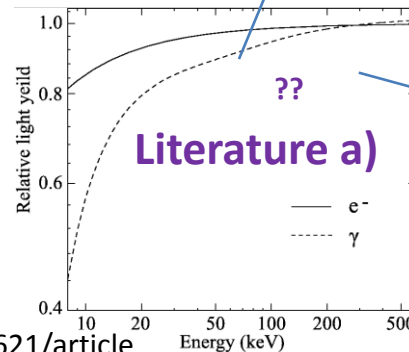
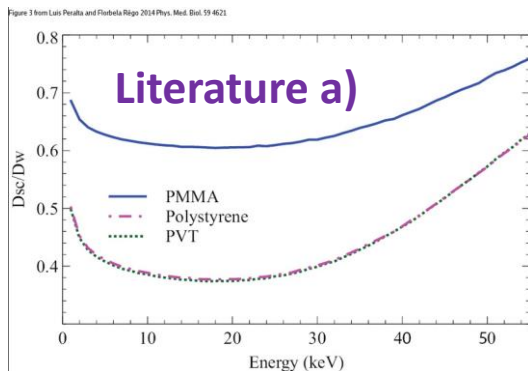
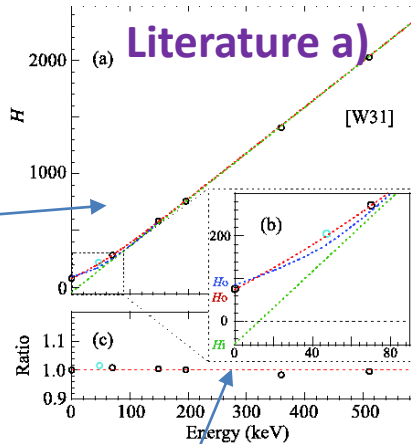
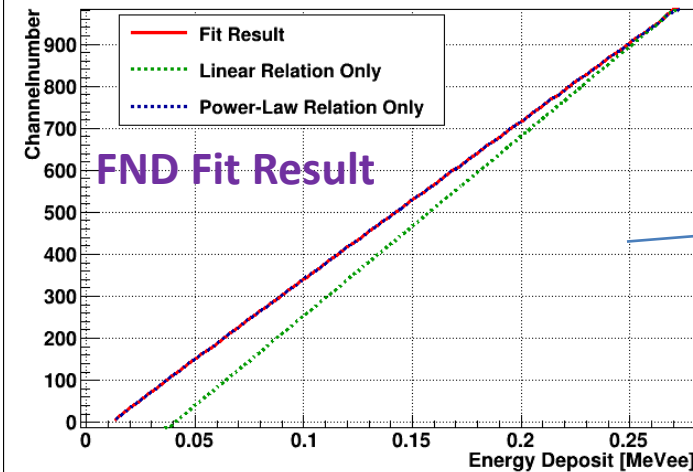


Fig. 4. Pulse calibration data for the rod-1 ADC and the associated gain-integrator assembly of the ABE detector.  $R$  denotes the range of amplification fed to the 6-bit ADC.

Feldman et al, NIM A 306 (1991) 350 ff

FND Channelnumber to Energy Deposit Conversion



Assumed linear

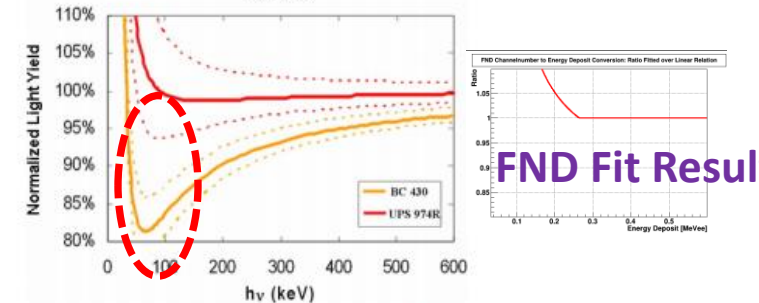
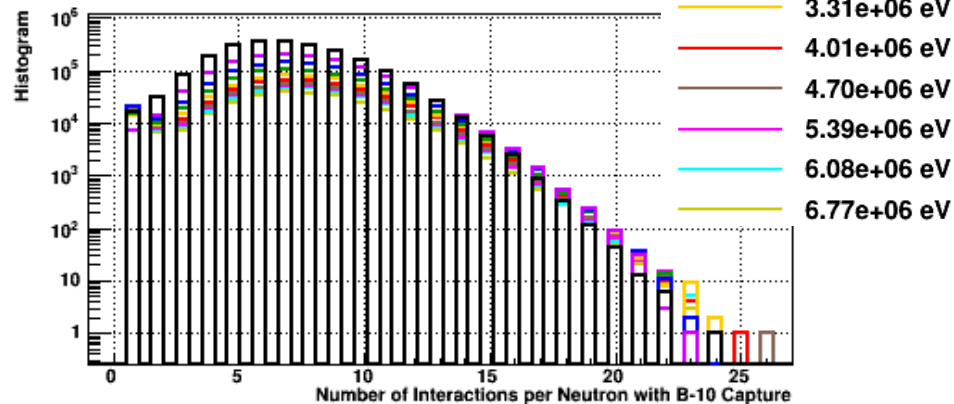


Fig. 11. Mean light amount for photons for the blue, green, and red scintillators (from top to bottom). The dotted lines represent the experimental uncertainties.

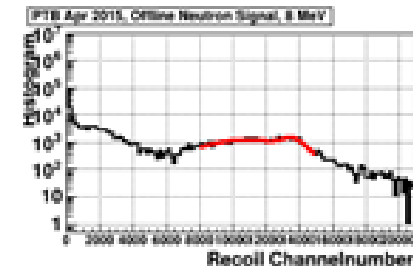
## 4. Scintillation Light Creation/Propagation: Light Function Formalism

### MCNP-PoliMi Scintillator Simulations

Number of Interactions per Neutron with B-10 Capture



### Exp. Recoil of 8 MeV Monoenergetic

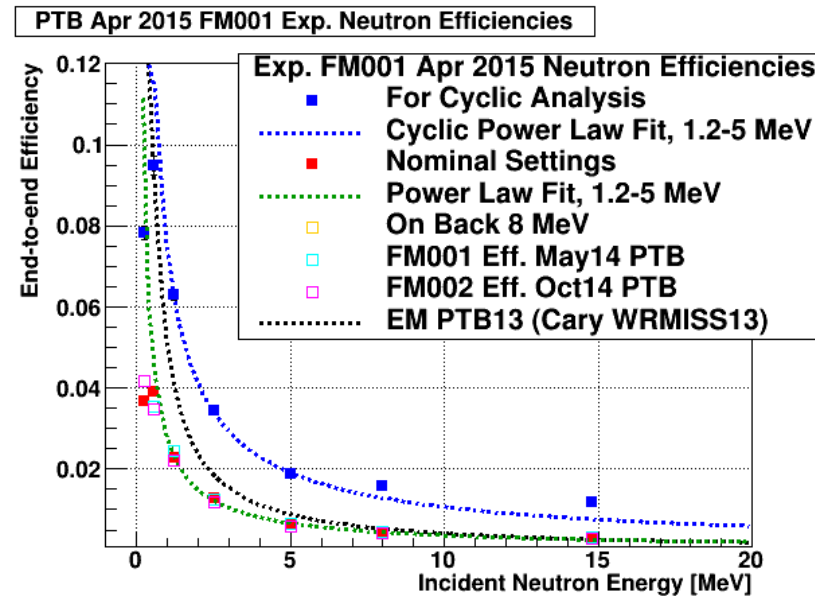


## **B: Misc Auxiliary Analysis Items**

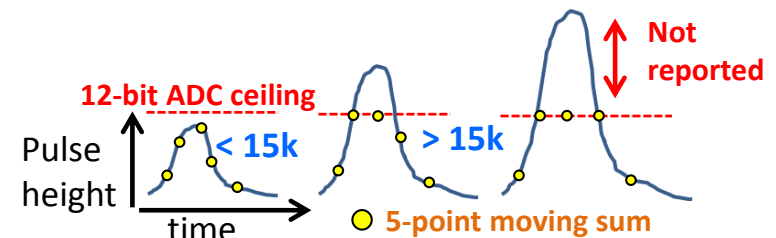
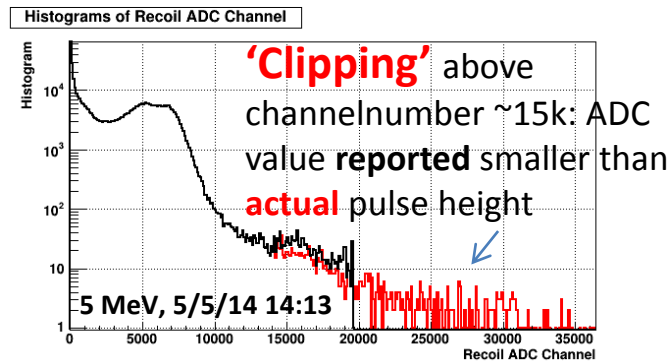


## 2) Neutron Efficiency Results, ADC Saturation

- Efficiencies from PTB datasets: Rel. uncertainties 2-3%;



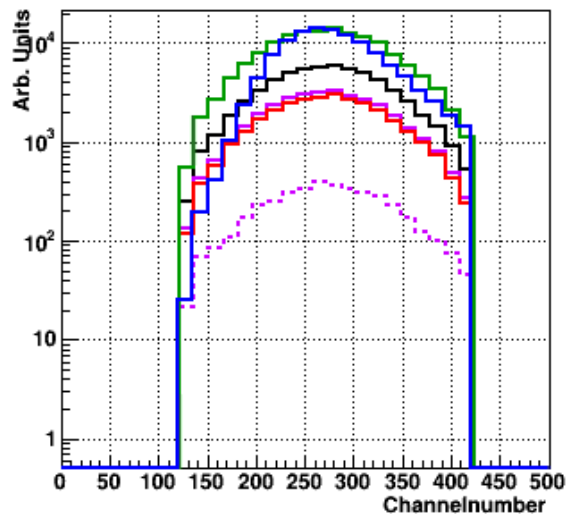
- ADC saturation for high pulse heights



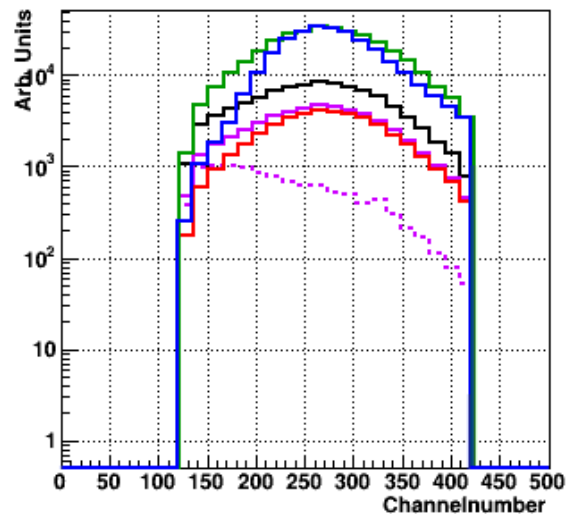
## 2) Preliminary Fit Result to Capture Pulse Distributions

- Experimental data not corrected for beam background/room return

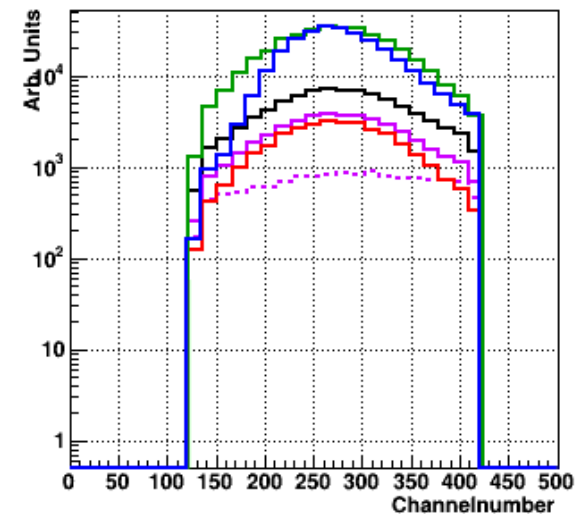
Neutron Candidate Capture Channelnumber Distribution, 0.25 MeV



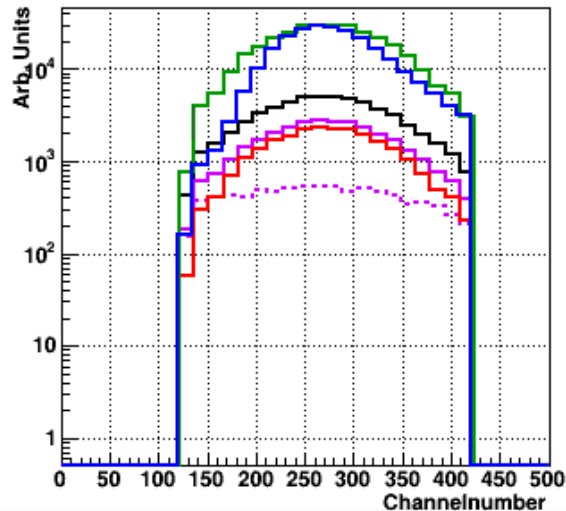
Neutron Candidate Capture Channelnumber Distribution, 0.5 MeV



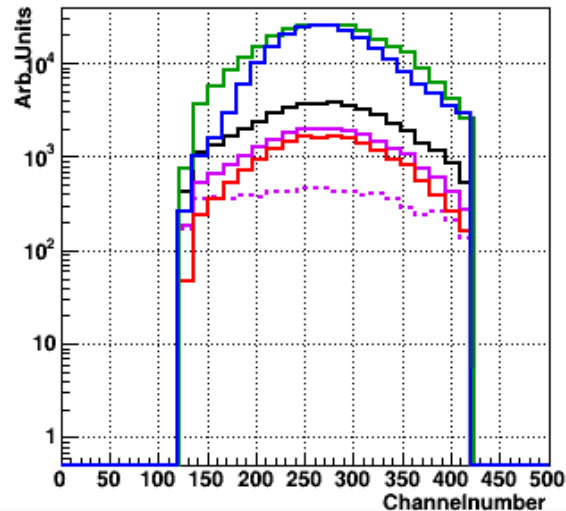
Neutron Candidate Capture Channelnumber Distribution, 1.2 MeV



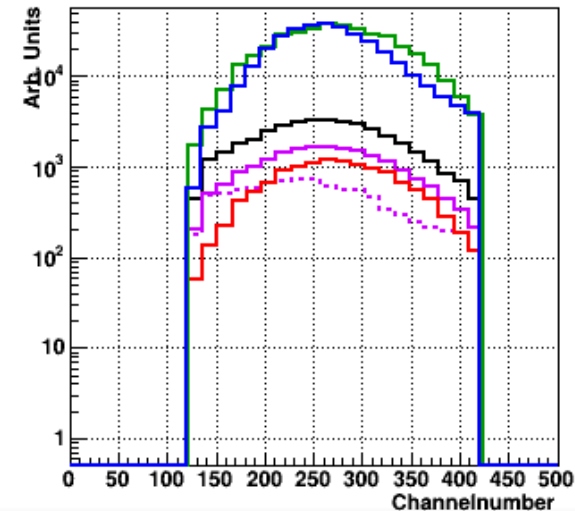
Neutron Candidate Capture Channelnumber Distribution, 2.5 MeV



Neutron Candidate Capture Channelnumber Distribution, 5 MeV



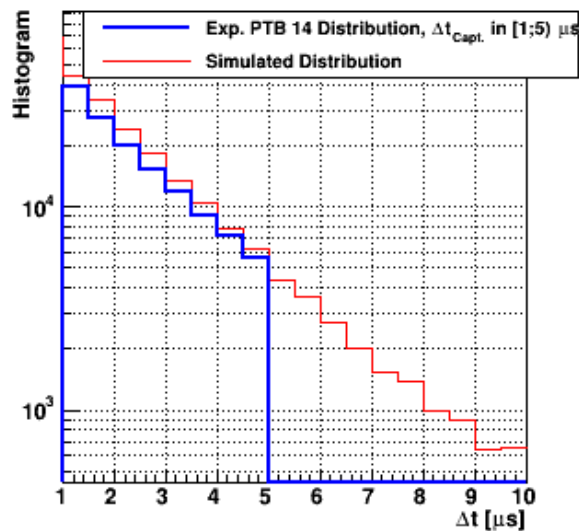
Neutron Candidate Capture Channelnumber Distribution, 8 MeV



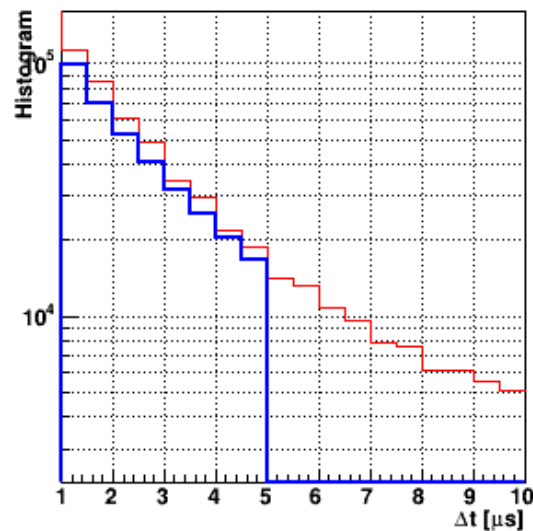
## 2) Preliminary Simulation Result for Delta t Capture Distribution

- Experimental data not corrected for beam background/room return

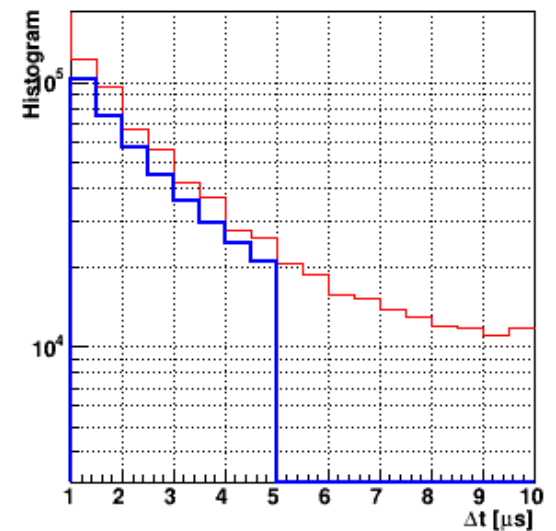
Neutron Candidate Capture  $\Delta t$  Distribution, 0.25 MeV



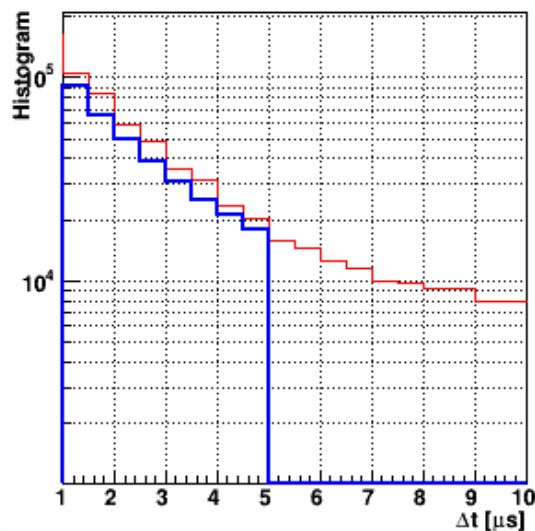
Neutron Candidate Capture  $\Delta t$  Distribution, 0.5 MeV



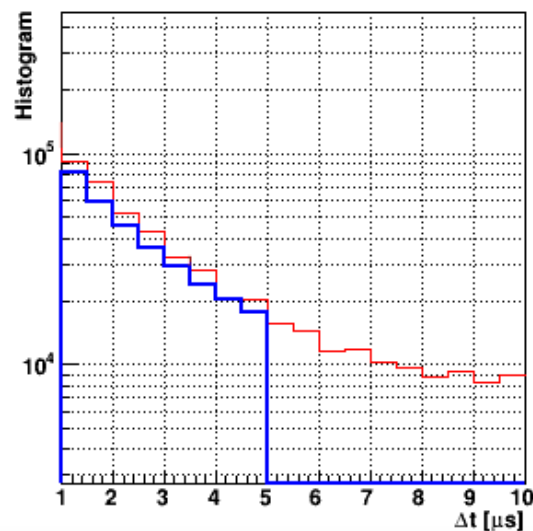
Neutron Candidate Capture  $\Delta t$  Distribution, 1.2 MeV



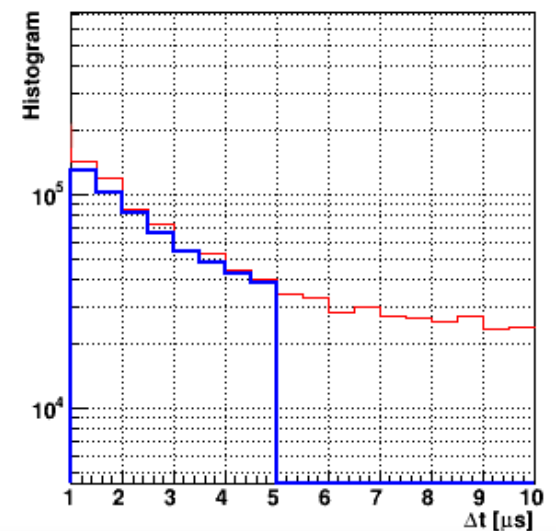
Neutron Candidate Capture  $\Delta t$  Distribution, 2.5 MeV



Neutron Candidate Capture  $\Delta t$  Distribution, 5 MeV



Neutron Candidate Capture  $\Delta t$  Distribution, 8 MeV



## B2) Test: AmBe vs. Distance, Extraction of Absorption Depth

- To be able to approximate FND as point detector

- fit doubles rates with shifted inverse squares:

$$f(d) = [0] + [1] * \frac{1}{(d + [2])}$$

\* only fit  $\geq 20$  cm data to avoid geometry issues (point source

approximation);

\* fit results:

@ [0]: background rate 0.5  $\pm$  0.07 Hz;

@ [2]: **effective absorption depth** of RAD = **7.2  $\pm$  0.5 cm**

\* deduce distance from JSC source to expose FND to roughly 50  $\mu$ Sv/hr for reference (neglecting room scattering, probably  $\sim 20\%$ ):

@ JSC calibration 5/21/14: source strength 2.380e+05 Hz;

@ with ICRP74 AmBe conversion factor 391 pSv\*cm<sup>2</sup> per n:

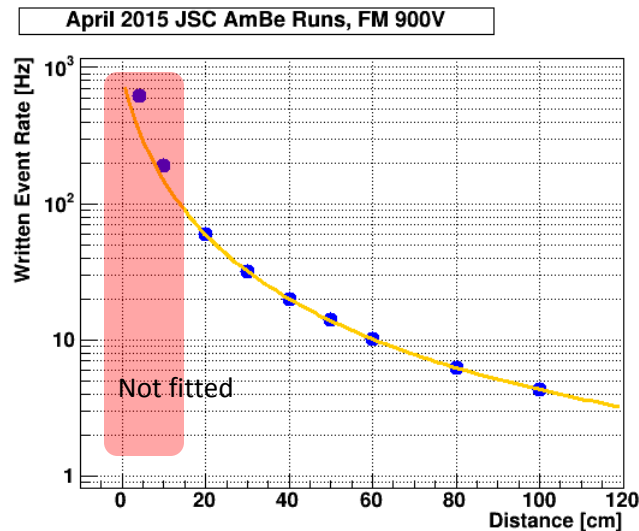
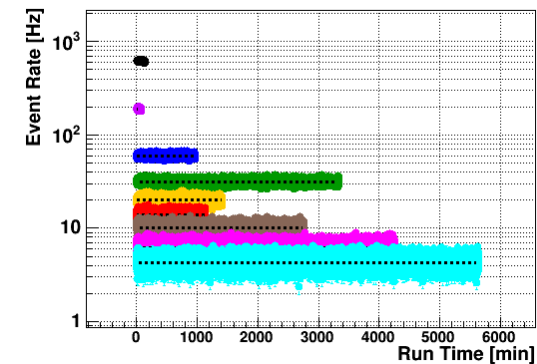
-> distance from absorption center to source = 23.1 cm;

-> distance from side of FND stack to source = **15.9 cm.**

### RAD FM, JSC AmBe vs. Distance

- 4 cm 3/18 14:15 UTC
- 10 cm 4/2 14:45 UTC
- 20 cm 4/1 22:42 UTC
- 30 cm 3/30 14:45 UTC
- 40 cm 3/19 14:29 UTC
- 50 cm 3/18 19:28 UTC
- 60 cm 3/23 14:42 UTC
- 80 cm 3/20 15:18 UTC
- 100 cm 3/26 16:21 UTC

Event Rate vs. Run Time, All Good Events



red chisq. of fit = 5.52/4 = 1.38